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TRANSACTIONS OF THE ACADEMY OF SCIENCES OF THE USSR, INSTITUTE OF EARTHS' MAGNETISM, THE IONOSPHERE AND RADIO WAVE PROPAGATION

(SELECTED ARTICLES)

UNEDITED ROUGH DRAFT TRANSLATION

TRANSACTIONS OF THE ACADEMY OF SCIENCES OF THE USSR, INSTITUTE OF EARTHS' MAGNETISM, THE IONOSPHERE AND RADIO WAVE PROPAGATION (SELECTED ARTICLES)

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TABLE OF CONTENTS

THE PROCEDURE FOR FORECASTING IONOSPHERIC AND MAGNETIC DISTURBANCES AND THE SHORT-RANGE FORECAST SERVICE AT IZMIRAN

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Introduction

Short wave radio communication is accomplished by the reflection of radio waves from the charged layers of the upper atmosphere, i.e., the ionosphere. The frequencies of radio waves which are reflected from the ionosphere are greatly dependent upon the electron density and altitude of the reflecting layers. Study of the regularities of the diurnal variation of the parameters of the ionosphere as functions of the season of the year, the geographical location of the point of reflection and of solar activity makes it possible to calculate the frequencies on which radio communication is possible. The calculation of the average monthly state of the ionosphere, i.e., for normal, undisturbed conditions, is the task of the so-called long-range forecasts, at the basis of which lies the existence of a relationship between the average monthly critical frequencies of the ionospheric layers and the moving leveled indices of solar activity. However,

radio waves with working frequencies calculated for normal conditions will not always be reflected by the ionosphere. This is due to the fact that the structure, density and altitude of the layers of the ionosphere can change greatly, deviating from the normal values. The significant changes in the ionospheric layers, connected with disturbances of the geomagnetic field, are due to processes in the active regions of the Sun. As a result of these processes, streams of particles (corpuscles) are ejected, which in some cases can reach the Earth. During ionospheric and magnetic storms, radio communication on those frequencies on which it was possible under normal, undisturbed conditions is often disrupted. But, if the frequency is changed accordingly, this disruption of communications can often be avoided.

The short-range radio forecast service is precisely intended for prediction of the periods of ionospheric and magnetic storms and the probable deviations of frequencies from their normal values. The forecasting is based on the use of running information on phenomena occurring on the Sun, in the Earth's magnetic field, and in the ionosphere, and is also based on the study of their interrelationships. The short-range radio forecase service was formed recently and the procedure for making forecasts needs further development and improvement. The fundamentals of the present procedure and the outlook for its development are given in this work.

1. The Nature of Ionospheric and Magnetic Disturbances

Solar activity is a source of ionospheric and magnetic disturbances. This activity is highly varied and leads to electromagnetic radiation over a wide range of frequencies, and to the ejection of particles of various mass and energy. Depending upon the agent

causing them, disturbances are divided into two types: wave and corpuscular.

Wave disturbances manifest themselves on the illuminated hemisphere of the Earth by sudden increases in short wave fade-out; brief, insignificant changes in the Earth's magnetic field; sudden phase anomalities in the long wave region; enhancement of atmospherics; and other brief effects.

Corpuscular disturbances cover the illuminated as well as the dark hemisphere. They manifest themselves by significant changes in the Earth's magnetic field, variation of the electron density and altitude of the ionospheric layers (chiefly the F_2-layer), and the disruption of short wave radio communications related to this. These disturbances are usually called ionospheric and magnetic storms.

A. Sudden increases in ionospheric absorption. The sudden enhancement of absorption in the lower layers of the ionosphere, leading to complete or partial disappearance of signals reflected from the ionosphere, is caused by an increase in the ionization of the D-layer under the influence of x-ray radiation emitted during chromospheric flares [1]. Inasmuch as the absorption of radio waves as they pass through a layer of the ionosphere (deflecting absorption) is inversely proportional to the square of the frequency, enhancement of absorption manifests itself more strongly at lower frequencies. A sudden increase in intensity can lead to complete or partial absorption of radio signals; with incomplete absorption, reflections begins from some minimum frequency f_{min}, which is considerably higher than the normal value of f_{min}. Absorption usually sets in suddenly and continues from several minutes to 1 to 2 hours, after which there is a gradual restoration of reflections, beginning from the high-frequency region and spreading to the lower frequencies. The

relationship between sudden increases in absorption and the conditions of the Earth's illumination by the Sun is dependent upon the highest probability of the appearance of flares during the summer and the increase in their intensity and duration with an decrease in latitude.

The frequency of chromospheric flares is closely connected with total solar activity and varies over an eleven-year cycle so that the maximum number of flares are observed during the years of maximum solar activity. The greater the intensity of a chromospheric flare, the higher the probability that it will cause ionospheric absorption.

Chromospheric flares cause a small, brief enhancement in the current system of smooth solar and diurnal geomagnetic variations, which appears on a recording as the so-called magnetic crochets.

Sudden increases in the intensity of absorption pertain to disturbances which are not predicted at the present time, just as the chromospheric flares causing them are not predicted. Some forecast centers give only the probabilities that chromospheric flares will be observed during a 24-hour period. This can be judged by whether there is an active region on the apparent solar disk and by how high its activity is.

B. Magnetic and ionospheric storms. The beginning of a magnetic storm is often observed a short time after a flare. The interval between a flare and the beginning of a magnetic storm is determined by the time necessary for corpuscles to pass from the Sun to the Earth. On the average, this is about 34 hours for flares of 3-point intensity and about 22 hours for flares with an intensity of 3+. The shortest recorded interval between a flare and the beginning of a storm is 17 hours [2].

A flare does not always precede a magnetic storm. Often magnetic

storms are observed after an active region has passed through the central meridian of the Sun. Storms caused by flares and storms caused by the passage of active regions through the central meridian differ essentially in the nature of their beginning as well as in their overall characteristics [3]. It has been established [4] that not all chromospheric flares affect the Earth. Flares related to the ejection of particles which affect the Earth are accompanied by sudden increases in solar radio emmission. The probability of the generation of a geomagnetic storm is a function of the intensity of the flare and the activity of the ejection, and also of the location of the source on the solar disk [5]. Geomagnetic storms caused by flares have, as a rule, a sudden beginning; they continue for 1 to 2 days (rarely longer) and are distinguished by considerable activity. These storms, for the most part, do not have 27-day periodicity.

Storms due to the passage of an active region through the central meridian have a gradual beginning, are of longer duration, are less intensive and have a well-expressed tendency toward 27-day periodicity. They are more frequent in years preceding minimum solar activity.

Geomagnetic disturbances are closely connected with disruption of the normal state of the ionosphere. At high latitudes, which are subject to direct intrusion of corpuscular streams, increased or complete short wave fade-out often sets in during disturbances. The strongest variations at the middle latitudes occur in the F_2-layer. Its electron density usually drops (i.e., the critical frequencies of radio waves reflected from it are lowered) and its altitude increases. As a result, the frequencies usually used for radio communications can be too high, signals will not be reflected by the layer, and communications will be disrupted. In addition, due to the

increase in absorption during disturbances, the lowest usable frequency (LUF) can be increased. Thus the range of useable frequencies is narrowed, which worsens communications conditions. The increase in the degree of diffusivity of reflections also contributes to worsening of communications during disturbances. However, by following the development of disturbances, and changing working frequencies correspondingly, it is possible to avoid disruption of communications in most cases (except in the case of very strong disturbances).

Sources of corpuscular streams. At the present time, it is assumed that magnetic and ionospheric storms are caused by corpuscular streams from the Sun. The following facts serve as the basic proof of this:

1) storms manifest themselves more strongly at high latitudes, where aurora polaris is often observed at this time; charged particles entering the sphere of influence of the Earth's magnetic field, moving along the lines of force of this field, penetrate precisely into these regions;

2) storms have a tendency toward 27-day periodicity, which is possible in the presence of beamed radiation, which includes corpuscular;

3) the beginning of a storm is delayed relative to an active process on the Sun for the time necessary for particles to travel the distance from the Sun to Earth;

4) studies made in the past years with artificial Earth satellites and space rockets have shown directly the presence of corpuscular solar streams which are responsible for ionospheric and magnetic disturbances;

5) in the aurora polaris spectra, the H_α-line is shifted to the short wave side, which attests to the presence of protons moving in the Earth's atmosphere from the Sun.

The question of the sources of corpuscular streams and of the mechanism of their ejection has been an open one up to the present time. However, many authors think that corpuscles are ejected from regions of the corona above the flocculi, due to the action of electromagnetic processes in the active regions [6]. The further movement of a stream is probably dependent upon the light pressure acting on it.

The presence of two types of storms and their characteristics force us to assume the possibility of the existence of two kinds of streams [7]: streams causing magnetic storms with gradual beginning, which cover the Earth with their lateral front, and streams causing storms with sudden beginnings, covering the Earth with their leading front. Calculation has shown that the density of matter in streams of the first kind near the Earth is of the order of several particles per cm^3, in streams of the second kind it of the order of several hundred particles per cm^3.

Study of the regularities of processes in the active regions of the Sun (especially of the magnetic fields in the active regions) allows the probability of ejection of a corpuscular stream to be evaluated [8].

2. The Characteristics of the States of the Magnetic Field and the Ionosphere

The degree of deviation of the magnetic field and the ionosphere from the normal, characteristic for the quiet, average state for a given season, geographical location and hour, is called the activity

of the magnetic field and the ionosphere. There are a number of characteristics for making a quantitative evaluation of the activity of the magnetic field. Depending upon the time interval over which the activity is characterized, they are divided into one-hour, three-hour and 24-hour characteristics.

The most generally used one-hour characteristic of the magnetic field is the three-point characteristic 0-1-2, which is given on the basis of the hourly amplitude of oscillations of elements of the magnetic field (the limits of these amplitudes for various points depend upon the geomagnetic latitude of the station) with a qualitative accounting of the nature of the oscillations.

The K-index of magnetic activity was introduced for the characteristic of the magnetic field over a three-hour interval. This is the ten-point characteristic from 0 to 9 (0-quiet, 9-strongly disturbed). It is determined by the value of the maximum deviations of a magnetic element from the quiet state. The index is determined by all three elements (H, D, Z), and the highest of these is chosen. The scales were developed differently depending upon the geomagnetic latitudes of the stations.

There is a generally used scale for the 24-hour characteristic: 0-1-2 (0-quiet, 2-strongly disturbed). The 24-hour index A_k came into wide use during the IGY. It was developed from the points of the K-index for 24 hours and is equivalent to the 24-hour amplitude expressed in units of 2γ.

There are no generally used indices of ionospheric activity. This is due the lack of knowledge of ionospheric disturbances, as well as their great diversity: changes in critical frequencies and altitudes, the appearance of sporadic layers, increase in absorption,

diffusivity, etc. This makes it difficult to develop a single index of ionospheric disturbance.

For high latitudes, at the Arctic and Antarctic Scientific Research Institute the 24-hour activity is characterized by the total number of cases of disturbance of the normal state of the ionosphere, which manifests itself in shielding of the F_2-layer by a sporadic E-layer, by the total absence of radio wave reflection from the ionosphere, partial fade-out, great diffusivity, and considerable lowering of f_oF_2.

For the middle latitudes, the main factor influencing radio communications during disturbances is the lowering of f_oF_2. The other above-mentioned factors definitely affect communications at the middle latitudes during disturbances, but for the ionospheric characteristic a the middle latitudes we can limit ourselves to deviations of f_oF_2 from the normal values (Δf_oF_2). Therefore, the characteristics used for short-range forecasting at IZMIRAN are based on values of Δf_oF_2.

Each hour is characterized by the value

$$\Delta f_o F_2 = \frac{f_oF_2 - f_oF_{2_{med}}}{f_oF_{2_{med}}} \cdot 100\%$$

In order to eliminate the effect on Δf_oF_2 of the seasonal variation of f_oF_2, during the month the moving median $(f_oF_{2_{med}})$ and not the monthly median is used as the normal value of f_oF_2. This moving median is calculated every 5 days (on the 5th, 10th, 15th, etc. of each month) according to the preceding 10 days. This median will be affected if there were disturbances for more than half of the 10 days. This occurs rather infrequently, so in most cases this median is characteristic of the quiet state.

The activity for each hour is evaluated according to the following scale by the value of Δf_0F_2:

Δf_0F_2,%	one-hour characteristic
0 – $\pm$10	0
+11 – $\pm$20	$\pm$ 1
+21 – $\pm$25	$\pm$ 2
+26 – $\pm$30	$\pm$ 3
+31 – $\pm$35	$\pm$ 4
	etc., up to $\pm$ 9

The sign of the characteristic corresponds to the sign of the deviation.

For convenience of comparison with the K-index, particularly for a graphical representation by a synoptic map of the Sun (which will be discussed below) , the three-hour interval is characterized by the highest of three values of Δf_0F_2.

In order to characterize the state of the ionosphere as a 24-hour average, 24-hour averages of all positive and all negative characteristics are made separately. In the quiet state both these averages are close to zero. If a disturbance is observed, the sign of the disturbance is usually retained for a 24-hour period and, therefore, one of the 24-hour-average characteristics will substantially exceed the other. Then the 24-hour periods are characterized by this highest point. In rare instances when a part of a 24-hour period was disturbed positively and a part negatively, the 24-hour period is given a double characteristic which preserves the sequence of the sign of the disturbance. For example, if during the first half of the 24-hour period frequencies were lowered and the average negative point was -2, and during the second half frequencies were increased and the average positive point was +3, then the characteristic for the day

is -2/+3.

Average deviations of f_0F_2 corresponding to 24-hour points are as follows:

24-hour characteristic	Average 24-hour Δf_0F_2, %
0	0 to ±10
$\pm$ 1	±11 to ±20
$\pm$ 2	±21 to ±25
$\pm$ 3	$\geqslant \pm26$

These ionospheric characteristics are purely conditional and do not give a complete representation of the degree of disturbance. They will be used to evaluate ionospheric disturbances at the middle latitudes until better characteristics are developed.

3. Regularities in the Appearance and Course of Disturbances

The eleven-year cycle. Both magnetic and ionospheric disturbances obey definite laws, the knowledge of which allows their beginning and development to be predicted. Inasmuch as disturbances are caused by active processes on the Sun, their beginning is subject to the same basic laws to which variation in solar activity is subject. Solar activity, as is well-known, varies with an eleven-year cycle. Therefore, eleven-year periodicity is also observed in the variation in the number and intensity of disturbances. Figure 1 shows the average annual sunspot numbers W and the annual number of magnetic storms N. A certain delay in the maxima of the number of magnetic storms relative to solar activity is observed. This is explained by the variation, during the eleven-year cycle, of the latitude of active formations on the Sun. The beginning of each new cycle is marked by the appearance of high-latitude formations, then they gradually shift to the low-latitude regions. This continues even after the

years of maximum solar activity. Then, although there are less active formations, the probability of corpuscular streams striking the Earth from them increases (the streams are assumed to be close to radial). As is apparent from Fig. 1, the delay in the maximum number of magnetic storms relative to maximum solar activity is about two years.

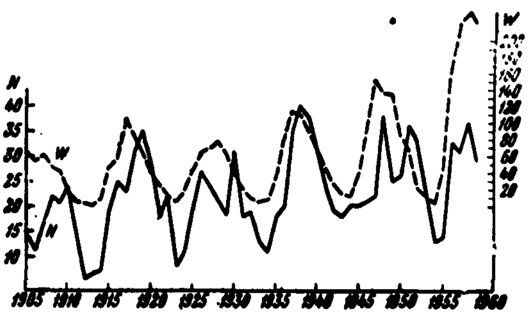

Fig. 1. Eleven-year cycle of solar and geomagnetic activity: W is the sunspot number; N the number of magnetic storms.

<u>Annual variation</u>. Ionospheric and magnetic disturbances are usually unevenly distributed throughout the year. They are more frequent and intensive in the equinox months. This is due to the fact that the Earth's orbit about the Sun is inclined at an angle of 7° to the solar equator, and during the equinox months the Earth is projected on the zones of highest solar activity. Therefore, the probability of corpuscular streams striking the Earth is greatest. Figure 2 shows the annual variation of the average number of magnetic storms N_{av} and the average number of days with negative ionospheric characteristics n_{av} for 1953 to 1959. The equinox maxima are clearly visible in both curves.

Fig.2. Annual variation in magnetic and ionospheric activity: N_{av} is the number of magnetic storms; n_{av} the number of days with negative ionospheric characteristics.

<u>Twenty-seven-day periodicity</u>. Magnetic and ionospheric disturbances tend to repeat at an interval which is a multiple of rotation time of the Sun about its axis (27.3 days). This tendency is expressed much more strongly in the years of minimum solar activity, which is explained by the greater stability of active regions during these years. Figure 3 shows negative ionospheric characteristics obtained from data from the ionospheric station at Moscow. Each row contains 27 days (a square corresponds to one day); the ionospheric characteristics for each day are placed in the squares (the appearance from time to time of an additional day in a row is due to the fact that the Sun makes one complete rotation in 27.3 days, not 27). As is apparent from this figure, stable sequences of disturbances are observed during the years of minimum solar activity (1953). For example, a disturbance for 16 to 26 days was repeated in the course of 5 rotations, from January to May 1953; a disturbance

for 7 to 13 days was repeated in the course of 7 rotations, from June to December 1953. During the years of maximum solar activity, such stable, prolonged sequences were not observed. Positive ionospheric characteristics are also grouped in sequences which manifest themselves more distinctly during the years of minimum solar activity.

The diurnal variation of disturbances. Just as there are diurnal regularities in the course of magnetic activity [9] (it is maximum in the evening hours), ionospheric activity, too, is unevenly distributed around the clock. A number of works [10,11] have been devoted to the study of this problem. N. V. Mednilova [12], in her study of the diurnal variation of ionospheric disturbances for the middle-latitude stations of the Soviet Union, examined it separately for positive and negative deviations. It was found that negative deviations have evening and pre-morning maxima in the winter and a daytime maximum during the remainder of the year. The maximum positive deviations are mainly observed during the night hours (all seasons). Figure 4 shows the diurnal variation [12] of positive and negative deviations Δf_0F_2 for the various seasons of the years of maximum and minimum for middle-latitude stations.

The diurnal distribution of the beginnings of ionospheric disturbances. It has been shown [12, 13] that ionospheric disturbances begin not at any time of the day, but mainly in the evening, night and morning hours, local time. The daytime periods when disturbances cannot start were called "prohibited" periods by Mednikova. The duration of the "prohibited" periods depends not only upon the height of the Sun above the horizon, but also upon the structure of the F_2-layer. Therefore, in the summer, when the daylight time increases,

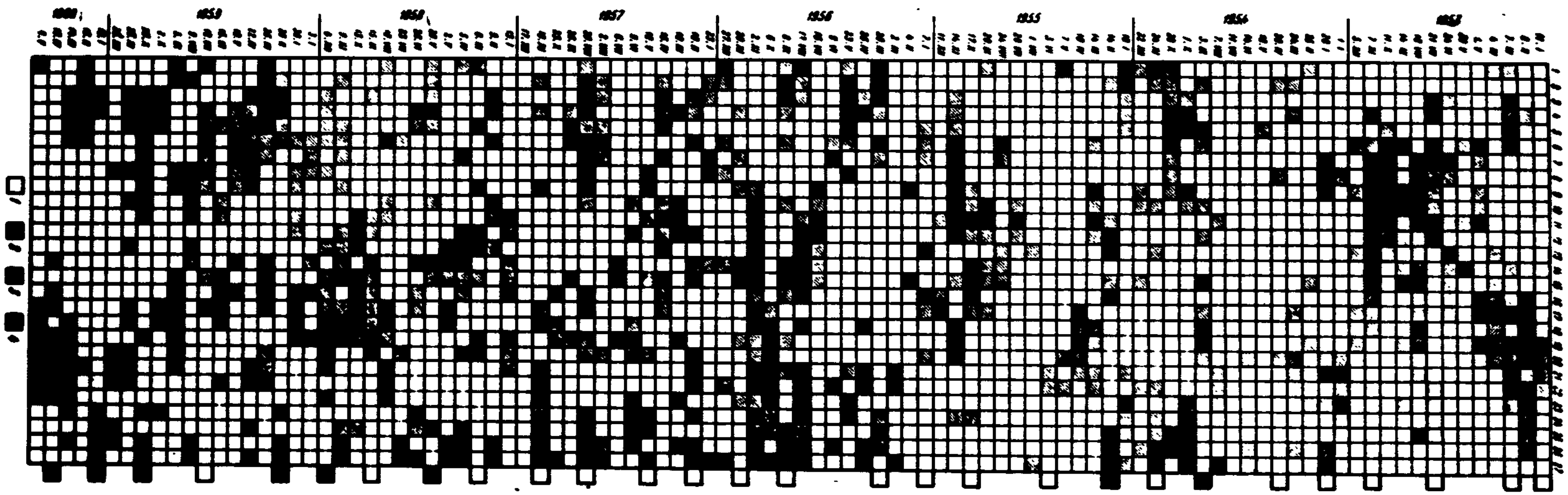

Fig. 3. The 27-day periodicity of negative ionospheric characteristics: 1) quiet; 2, 3, 4) weak, moderate and strong disturbance, respectively.

the prohibited periods begin not earlier, but later. This is due to the fact that in the summer this region is divided into F_1 and F_2 layers and becomes less stable. In Moscow, the "prohibited" periods in the winter last from 0600 to 1800, in the summer and at the equinoxes they begin at about 0800 and end between 1600 and 2000.

<u>The geographical distribution of ionospheric disturbances</u>. When examining the nature of ionospheric and magnetic disturbances, it was mentioned that one of the main arguments in favor of their corpuscular nature was the increase in the intensity of disturbances toward the high latitudes. Corpuscles flying from the Sun, falling into the sphere of influence of the Earth's magnetic field, move along its lines of force to the poles and enter the atmosphere at high latitudes, causing aurora polaris there. Therefore, disturbances are more frequent and stronger at high latitudes. Calculation of the average

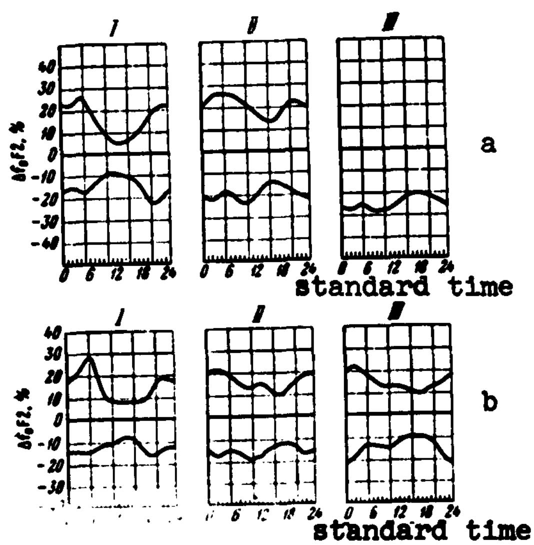

Fig. 4. The diurnal variation of positive and negative disturbances for the years of maximum (a) and minimum (b) solar activity [12]. I- winter; II- equinox; III- summer.

$\Delta f_o F_2$ for all the strong and very strong storms of 1947 showed [14] that it had a high negative value at high latitudes, decreased when moving to the low latitudes, became positive at latitudes of 20 to 30°, and remained positive at the equator. Such is the average picture of the latitudinal distribution of ionospheric disturbances. In each individual case, the disturbance is more complicated, and the geographical distribution cannot be represented by such a simple rule.

4. The Fundamentals for Predicting Disturbances and Problems in the Area of Further Development of the Method

The known regularities in ionospheric and magnetic disturbances allow the time of appearance and the course of disturbances to be predicted. The relationship between disturbances and solar phenomena serves as the basis for these forecasts. Therefore, the observation and study of solar activity make it possible to predict the appearance of disturbances.

The tendency toward 27-day periodicity makes it possible to predict disturbances almost a month in advance. A "rug" of ionospheric characteristics (Fig. 3) is used when making these forecasts, and the singularities of each series of disturbances are taken into account. When the disturbances were of recent origin and intensive, their repetition and intensification could be expected in the course of 2 to 3 rotations; then, usually, the intensity of disturbances of a given series gradually decreased.

When making a forecast for a shorter period of time, it is possible to take running information on solar activity into account. As indicated in Section 1, electromagnetic processes in the active regions of the Sun are a source of corpuscles which affect the Earth [8]. A change in the magnetic field in an active region induces an

electrical field. The action of these two fields can cause a Hall current, the direction of which is a function of the direction of the magnetic field as well as of the nature of its variation (increase or decrease). If this current is beamed from the Sun, then particle ejection can occur. Otherwise, the conditions for stream ejection are not created in the active region.

Observations of processes in active regions allow their effect on the Earth to be judged. However, at the present time the study of the electromagnet processes in active regions is in the stage of setting up experiments and preliminary processing. Obtaining operational information on the magnetic field of active regions is a matter for the near future. This should considerably lighten the task of predicting disturbances and improve their quality.

However, even without information about the magnetic fields, it is possible to make a qualitative judgement about them with information from solar observatories: variations in sunspot area, flocculi, the quality and intensity of chromospheric flares, etc.

In order to represent the entire aggregate of active formations in a form which is convenient for forecasting, synoptic maps of the Sun are used (Fig. 5). A synoptic map, which is the working map for making forecasts in the department of short-range radio forecasts at IZMIRAN, is limited to the range of latitudes from 60° N to 60° S, since active formations are very rare at higher latitudes. The longitudes on the map are Harrington's longitudes. The dates of the passage of each longitude through the center of the apparent solar disk are written under the map. Thus, by knowing the coordinates of an active formation and plotting it in the proper place, it is possible to determine when it will reach the central meridian.

The delay of disturbances relative to the passage of an active region through the central meridian can vary according to the velocity of the stream and its deflection by the magnetic field. It is from 1 to 2 days, rarely longer. It is known that a disturbance often follows 1 to 2 days after a strong chromospheric flare; the disturbance being due to the ejection of corpuscles during the flare. It has recently been shown [15,16] that the flares which affect the Earth the most are accompanied by bursts of radio emission, especially in the meter range. The so-called type-IV bursts are given great significance here. A high degree of polarization, long duration and a close connection with strong chromospheric flares are characteristic of these bursts. The times and intensity of chromospheric flares and bursts of radio emission, and also the magnetic (K-index) and ionospheric (Δf_0F_2 maximum for three hours) characteristics are given under the synoptic map (Fig. 5) for convenience of forecasting. Observations of solar activity allow predictions of the state of the magnetic field and ionosphere to be made for a period of 1 to 7 days (7 days is about one-fourth of the period of the Sun's rotation).

Besides data on the Sun, for forecasting of ionospheric conditions information on the magnetic field and running ionospheric data are used. Magnetic disturbances in the middle latitudes, as a rule, begin before ionospheric disturbances. Therefore, the beginning of a magnetic disturbance usually allows one to expect disruption of the normal states of the ionosphere within the next few hours. Information obtained from ionospheric stations allows the movement of the centers of ionospheric disturbances to be judged. The beginning of an ionospheric disturbance in the North (frequently manifesting itself by anomalous or complete absorption) is also often an harbinger

of an ionospheric disturbance in the middle latitudes.

Thus, the aggregate of information on solar activity and geophysical phenomena allows ionospheric and magnetic disturbances to be predicted.

At the present time, more and more attention is being given the study of the electromagnetic processes in the active regions of the Sun. Inasmuch as the atmosphere in the active regions of the Sun (in the chromosphere and corona) is a plasma, the determining forces in it are magnetic and induced electrical fields. The possibility of ejection of a corpuscular stream and its generation are dependent upon variations in these fields. Therefore, prediction of the intensity of disturbances and their nature can be accomplished only after studying quantitatively the variation of the magnetic fields in the active regions at various levels of the solar atmosphere. A qualitative evaluation of the variation in the electromagnetic fields in the active regions can be made from the changes in the various characteristics of solar activity: sunspot area, the intensity of solar radio emission in various frequency ranges, etc. A study of the variation in these characteristics during the periods preceding storms is being conducted at the present time at IZMIRAN. It is hoped that this study will help in finding the best harbinger of disturbances.

Besides predicting the appearance and intensity of a storm, which is done on the basis of observations of various manifestations of solar activity, for successful radio communications it is necessary to know the frequencies on which communication is possible during disturbances. Prediction of radio communications frequencies comes down to extrapolation of a series of observed values of ionospheric

parameters.

The possibility of forecasting frequencies for radio communications during disturbances has been examined [14]. It has been shown that Δf_0F_2 during disturbances can be great, but it undergoes strong fluctuations, and during the course of several (3 to 4) hours it becomes stable. This makes it possible to predict frequencies by extrapolation. The average error of these predictions is about 0.5 Mc.

Study of the geographical distribution of ionospheric disturbances plays an important role in quantitative forecasting. A work in the present collection [17] examines the spatial distribution of disturbances chiefly in the middle latitudes. A study of the spatial distribution of disturbances makes it possible to interpolate f_0F_2 during disturbances.

Least of all studied is the geographical distribution of ionospheric disturbances in the high latitudes, where disturbances are more frequent and intensive and differ from those in the middle latitudes. For the high latitudes it is insufficient to study deviations Δf_0F_2 during disturbances; it is necessary to examine the variations occurring in the lower layers of the ionosphere. The results of preliminary work carried out at IZMIRAN in the study of disturbances at high latitudes are given in another work in this collection [18].

The observations during the IGY and IGS, which were made by a large network of stations and which were especially frequent during the special world intervals, are a great contribution to the study of disturbances. Further processing of this material, already used in a number of works [17,18], will make it possible to deepen our knowledge of the space and time regularities of disturbances, and thereby to improve the procedure for their prediction.

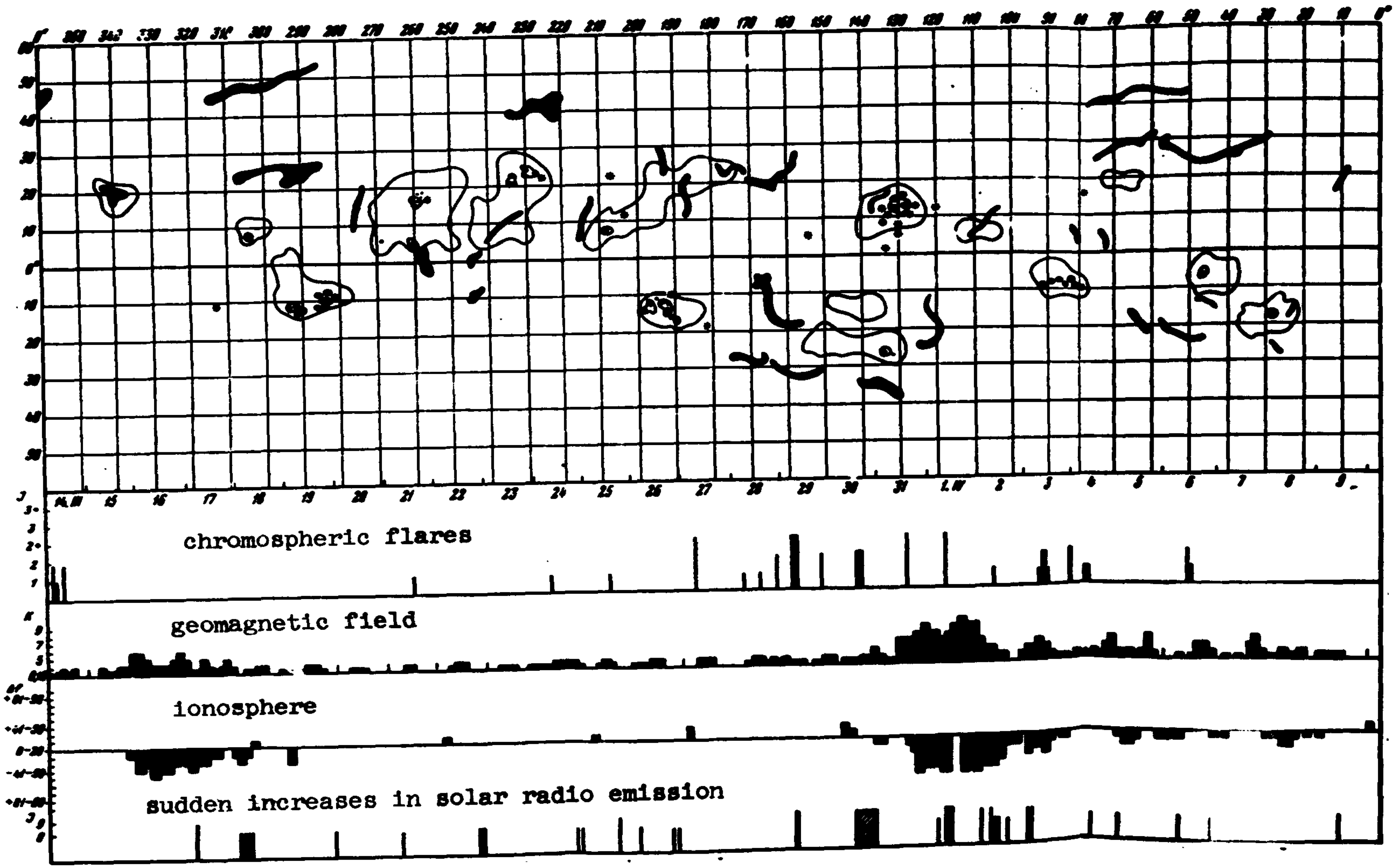

Fig. 5. Working graph used for making forecasts

5. The Short-Range Forecast Service at IZMIRAN

On the basis of the above relationships and regularities, the following telegraph information is used for forecasting:

1) the sunspot coordinates and areas, from the observatory at Kislovodsk;

2) the coordinates, areas and intensity of calcium flocculi, from the observatory at Simeize;

3) the time, coordinates and intensity of chromospheric flares, from solar observatories in the USSR and abroad (in all about 15 observatories);

4) observations of the level of radio emission and sudden increases in its intensity in various frequency bands at 9 observatories at various parts of the Earth;

5) information on sudden ionospheric disturbances (sudden increase in absorption) from 15 stations in various countries;

6) ionospheric data from stations in Murmansk, Tomsk, Ashkhabad (hourly); Yakutsk, Sverdlovsk, Bukhta Tikhaya, Buxhta Tiksi, Dixon, Irkutsk, Alma-Ata, Leningrad (once every three hours, hourly data); Peking, Chungking, Kwangtung (Communist China; once every six hours, hourly data); daily summaries of hourly data: Budapest, Prugonice (Czechoslovakia), Juliusruch (East Germany); three-hour data are given once a day from the Khabarovsk station; from Lindau (West Germany), Fort Belvoir (USA), Kokubunji (Japan), six-hour data are given daily, and, finally, the station at Rostov has sent median data every 5 days for the past decade.

Besides telegraphic information, observations made at IZMIRAN of the photosphere and chromosphere of the Sun, the Earth's magnetic field and of the ionosphere are used. The following forecasts are

made by processing and analysis of these data: monthly, five-day and twelve-hour. The monthly forecast is mailed five days before the beginning of the month to interested organizations; the five-day and twelve-hour forecasts are included in the summaries sent daily by radio. Table 1 gives the schedule of radio transmissions an some information about the transmitters.

Radio transmissions of space data include the following information:

pyatso-sunspots (coordinates and areas of groups of spots and the sunspot number of the day);

vspso-solar flares (coordinates, intensity and duration of chromospheric flares);

khroso-solar chromosphere (coordinates, areas, intensity and duration of calcium flocculi);

kroso-solar corona (information on the active sections in the green, yellow and red lines);

rshuso-solar radio noise (data on the average intensity level and sudden increases in the intensity of solar radio emission);

vnivo-sudden ionospheric disturbances (their time and intensity);

magkha-magnetic characteristics (three-hour K-index of magnetic activity and diurnal A_k-index, and also information on the beginning and end of magnetic disturbances);

ionda-ionospheric data from the Moscow station (f_oF_2 and F_2-3000 MUF);

ionkha-ionospheric characteristics for the last 12 hours and the forecast for the next 12 hours;

prooch-forecast of optimum working frequencies, given once every five days (on the 5th, 10th, 15th, etc. of the month) and

containing the expected numerical characteristics for Δf_oF_2 for the next five days. The radio transmissions of ionospheric data include f_oF_2 and F_2-3000 MUF for every even hour at Moscow, median data for f_oF_2, F_2-3000 MUF and E-2000 MUF once every five days, and a five-day forecast of the level of optimum working frequencies (prooch).

Table 1

Moscow legal time	Transmission mode	Call signs	Freq., Mc;	Antenna	Data transmitted
08^{30}–08^{40}	Radio telegraph	RDZ-73 RND-78 RBI-72	9855 5340 16135	Dipole Dipole Directed toward Irkutsk	Space data and forecast Space data and forecast
20^{28}–20^{30}	Radio telegraph	RDZ-73	9855	Dipole	Space data and forecast
		RDZ-73	10050	Dipole	
02^{15}–02^{45}	Radio telephone	GAMTs	3937,5 4395 5780 6980		Ionosphereic data and forecast
14^{05}–14^{40}	Radio telephone	GAMTs	5380 7450 9145 13360		Ionospheric data and forecast

According to inquiries, the maximum usable frequencies for radio communications are calculated for the next few days and information is given on the running state of the ionosphere and the magnetic field. Figure 6 gives a diagram of the forecast and information service of IZMIRAN.

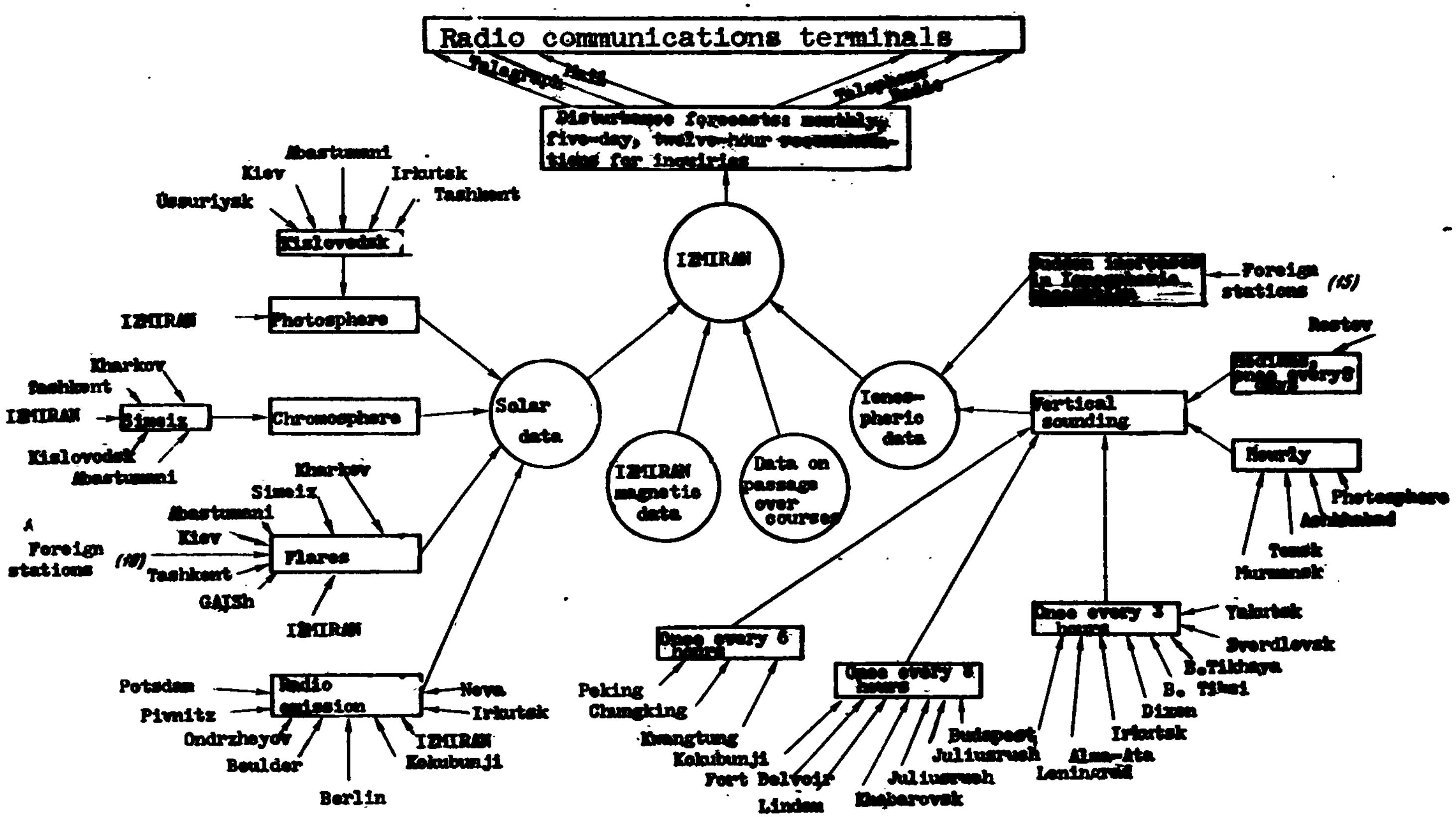

Fig. 6. Diagram of forecast and information service of IZMIRAN.

Conclusions

The percentage of valid forecasts serves as an objective evaluation of the quality of the forecasts. On the average, for 1957-1958, 66% of the monthly forecasts, 70% of the five-day forecasts, and 86% of the twelve-hour forecasts were valid (with accuracy up to 1 point).

The procedure for forecasting ionospheric and magnetic storms needs further development. Primarily, this pertains to the study of helio-geophysical relationships. The years of the IGY and IGS, when an international exchange of data and the "Alert" service were organized, and the years of the special world intervals (SWI), showed that the recommendations of various forecast centers, by announcement of the SWI, agreed with the disturbances, on the average, only in 30% of the cases. The procedure and level of forecasts in various countrie was about the same.

It may be hoped that the rich material of observations from the IGY and IGS during the SWI which coincide with ionospheric and magnetic storms will, after processing and study, be a valuable contribution to the study of the space and time regularities during disturbances. It is also necessary to study the active processes on the Sun which cause disturbances. Further study of electromagnetic processes in the active regions is particularly necessary.

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IONOSPHERIC DISTURBANCES AT HIGH LATITUDES AND THE POSSIBILITY OF FORECASTING THEM

R. A. Zevakina

At middle and low latitudes the critical frequencies and altitudes of the F2 layer undergo the greatest changes during disturbances. Moreover, at high latitudes the condition of the lower ionosphere is severely altered. There is a significant increase in the ionization density in the absorption region (at an altitude of 60-80 km), which leads to increased or total absorption of short radio waves and to the appearance of clouds having a high ionization density in the E and F regions (Es and F2s). For these reasons a deterioration or complete disruption of radio communication is often observed at high latitudes.

Despite the great amount of work done in investigating the ionosphere at high latitudes [1-12 and others], our knowledge of the development and propagation of disturbances in space is, as of the present time, very limited. Owing to the insufficient network of ionospheric stations at high latitudes, the zone of polar absorption, which appears to be the primary cause of the disruption of radio communication, has not yet been accurately determined, and the geographical distribution of Es and the anomalous variations in the F2 region are not altogether

clear.

As a result of ionospheric observations carried out by a network of stations in the Arctic and Antarctic during the International Geophysical Year, a more thorough study of the ionosphere and, in particular, ionospheric disturbances is now possible.

The present article sets forth the features of ionospheric disturbances at high latitudes and the preliminary results of an investigation of their geographical distribution according to IGY data. Moreover, the question of forecasting disturbances at high latitudes is given consideration.

Before proceeding to a description of the disturbances, let us briefly recall the features of the calm state of the high-latitude ionosphere.

1. Brief Characteristic of the Calm State of the Ionosphere at High Latitudes.

Regular diurnal and seasonal variations in the parameters of the F2, F1, and E layers and their dependence on the level of solar activity are, in general, the same at high latitudes as at middle latitudes. The only special features are those associated with the specific conditions of illumination of the high-latitude ionosphere by the sun. Thus, because of the lower elevation of the sun, the general level of ionization of all regular layers of the ionosphere is lower at high latitudes than at middle latitudes. In years of low solar activity the values of foF2 during the morning and evening hours of the winter months under calm ionospheric conditions are often less than the lower limit of the frequency range of the ionospheric stations (i.e., less than 1-1.5 Mc). As a result, it is sometimes impossible to establish

short-wave radio communication. During a polar day, the diurnal variation of foF2 is not pronounced. Therefore radio communication can be maintained on one and the same frequency during the entire day. During a polar night the diurnal variation of foF2 has, as at middle latitudes, a maximum after noon.

The E and F1 layers are observed around the clock during a polar night. Their ionization density, as in the case of middle latitudes, is proportional to the cosine of the zenith distance of the sun.

At high latitudes during the equinoxes and during most of the winter months disturbed days occur more often than calm ones. Consequently, the median values of foF2 for all days do not characterize the calm state of the ionosphere. The latter is determined by the median values of foF2 calculated for only the calm days of the month [2]. The calm days are usually selected according to the condition of the geomagnetic field. However, at high latitudes on magnetically calm days the ionosphere may be disturbed; it is therefore better to select calm days according to the condition of the magnetic field and of the ionosphere. The medians with respect to calm days are higher than the medians for all days, which attests to the fact that during periods of disturbances the values of foF2, in most cases, decrease.

The E and F1 layers are subject to very few disturbances; therefore the monthly medians for foE and foE1 correspond to the values for calm days.

2. Characteristics and Peculiarities of Ionospheric Disturbances at High Latitudes.

During periods of disturbances at high latitudes an anomalous absorption and a significant increase in the limiting Es frequencies

are observed most often. As a result of complete absorption or of the shielding action of the Es layer, the F2 region is observed comparatively seldom during disturbances, especially in years of low solar activity.

By anomalous absorption is meant an increased ionization, which is registered by ionospheric stations as a significant increase in the values of f_{min} (minimum frequency reflected from the ionosphere) or the absence of reflected signals (complete absorption).

The measurement of the absorption of radio waves in the ionosphere is carried out at a very limited number of points; therefore for a relative estimate of the magnitude of the absorption it is necessary to use the values of f_{min}. It is known that f_{min} depends not only on the magnitude of the absorption in the ionosphere, but also on the characteristics of the equipment (power, amplification, the lower limit of the frequency range of the station, etc.). The lower limit of the frequency range of most stations is approximately the same (equal to about 1 Mc).

Variations of f_{min} which depend on the parameters of the equipment are insignificant in comparison with the magnitude of the variation of f_{min} as a result of anomalous absorption; therefore, if we consider the deviations of f_{min} from normal values, they can serve as a characteristic of the variation of the absorption.

At present there is no generally accepted criterion for estimating the increased absorption and the limiting Es frequencies corresponding to a disturbed state of the ionosphere. Several investigators [3,12] consider the absorption increased, if f_{min} exceeds 3.0-3.5 Mc, Diurnal and seasonal variations in f_{min} are not taken into account in such an estimate. In order to take these variations into account, it is better to estimate the absorption on the basis of the deviation

of f_{min} from the medians. Since f_{min} increases during disturbances, the monthly medians for all days during the disturbed months are overstated by 20-40% in comparison with the medians for calm days. Hence, in order to estimate the absorption, we used the quantity $\Delta f_{min} = f_{min} - (f_{min})_{med}$, where $(f_{min})_{med}$ was calculated for calm days.

Analysis of Δf_{min} with respect to the data of a large network of stations during the period of IGY and comparisons of Δf_{min} with other characteristics of the disturbances indicated that absorption may be considered increased, if Δf_{min} exceeds 40%.

At high latitudes E_s clouds are permanent. However, the density of ionization and the dimensions of the clouds vary greatly in time.

During a quiet period the limiting Es frequencies do not exceed 3-4 Mc. During disturbances the values of fEs increase, often reaching 7-10 Mc. Comparison of fEs with other characteristics of disturbances of the ionosphere and also with the composition of the geomagnetic field indicates that fEs $\geq$ 4 Mc corresponds to a disturbed state of the ionosphere [12].

It is general practice to estimate the anomalous variations of foF2. Deviations of the observed values of foF2 from the median values in excess of 20% for calm days and for a given hour indicate a disturbed state of the F2 layer at middle and high latitudes. Moreover, a cloud-like structure is characteristic of a disturbed state of the F2 layer at high latitudes. As a result of the cloudiness, reflections from the F2 layer are diffused, and sporadic F2s clouds are observed. Reflections from the F2s layer are usually observed at the same altitudes as the basic layer, but the limiting F2s frequencies, as a rule, significantly exceed foF2. F2s clouds are most frequently observed during the nighttime hours of the winter months. The frequency of

their appearance increases with an increase in solar activity [7,8].

Thus the basic characteristics of a disturbed state of the ionosphere at high latitudes are total (B) and increased ($\Delta f_{min} > 40\%$) absorption, an increase in the limiting frequencies fEs above 4 Mc, deviations of foE2 from normal values in excess of 20%, and the appearance of F2s.

During disturbances at high latitudes variations are observed throughout the entire thickness of the ionosphere. Only in some cases the lower ionosphere is subject to great variations and in others - the upper ionosphere. Consequently, A. S. Besprozvannaya [3] divides ionospheric disturbances into two types: 1) FD-disturbances, when disturbances are observed in the lower ionosphere at the same time with anomalous variations in the F region; 2) F-disturbances, when anomalous variations are observed mainly in the F region. During F-disturbances anomalous absorption (B and $f_{min} \geqslant 3.5$ Mc) is observed for not more than eight hours out of twenty-four.

As a result of an investigation of FD- and F-disturbances in accordance with the Tiksi Bay data for 1946-1955, A. S. Besprozvannaya drew the following conclusions [31]. F-disturbances change during the course of a solar cycle similar to magnetic storms of sudden origin, while FD-disturbances are similar to magnetic storms of gradual origin. The maximum F-disturbances occur during years of high solar activity (1948-1949), while the maximum FD-disturbances occur during years of abatement of solar activity (1951-1952). Their seasonal variations also differ. FD-disturbances have distinctly pronounced equinoctial maxima, while F-disturbances, have a summer maximum, as well as the equinoctial maxima. The division of ionospheric disturbances into the two types mentioned is very arbitrary. In the work referred to [3], disturbances are not considered, when total absorption is observed for

an extended period (over a period of several days). However, the difference detected in the patterns of F- and FD-disturbances is of great interest.

3. Diurnal and Seasonal Variations of Ionospheric Disturbances. Twenty-Seven Day Periodicity.

The nature of the anomalous phenomena of the ionosphere changes during the course of disturbances in accordance with the hour of the day. During the daytime hours complete and increased absorption is observed; during nighttime hours an Es with high limiting frequencies and anomalous variations of foF2 are observed. By way of illustration, Fig. 1 shows the diurnal variation of frequency, appearance of total (B) and increased ($f_{min} \geq 3$ Mc) absorption, fEs ≥ 4 Mc, positive and negative ΔfoF2 > 20% during 1957, according to the data of the ionospheric station at Murmansk [12]. The greatest frequency of the appearance of complete absorption occurs in the morning hours, that of increased frequency at noon, and fEs ≥ 4 Mc at midnight. The diurnal variation of positive and negative ΔfoF2 > 20% is not so clearly expressed, the frequency of their appearance being somewhat high in the evening hours (zone time). Such a distribution of ionospheric disturbances during the course of the day is characteristic of other high-latitude stations as well [1-8].

The diurnal variation of ionospheric disturbances depends on the distance from the zone of maximum frequency of polar auroras. According to A. P. Nikol'skiy's data [13] isochrones of the morning maximum of the magnetic disturbances and the maximum frequency of the appearance of total absorption appear as a system of spirals radiating out from a pole of uniform magnetization of the earth.

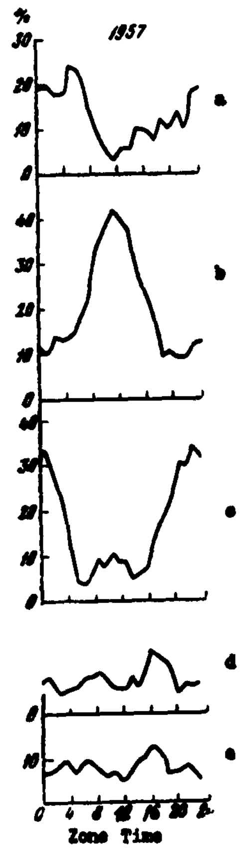

Fig. 1. Diurnal variations in the frequency of the appearance of: total (a) and increased (b) absorption; fEs $\geq$ 4Mc (c); positive (d) and negative (e) $\Delta foF2 > 20\%$ (Murmansk, 1957).

The diurnal variation of the frequency of the appearance of Es north of the polar-aurora zone has two diurnal maxima, while within

the aurora zone it has one midnight maximum [6]. This dependence in polar coordinates, according to Ye. I. Dolgova's data [14], has the form of two spirals. One of them, the evening spiral, unwinds in a counterclockwise direction, while the other, the morning spiral, unwinds in a clockwise direction. The moments of greatest frequency of appearance of disturbances in the F2 layer, according to Dolgova's conclusions, are located along three spirals. Two of them coincide with the spirals of greatest frequency of appearance of Es. These conclusions were obtained on the basis of scant material and therefore require further verification.

A dependence on the time of day is revealed in the occurrence of ionospheric disturbances. At middle latitudes there are prohibited periods, i.e., intervals of time during which ionospheric disturbances do not begin [15]. At high latitudes the same kind of regularity is observed in the appearance of disturbances; however, the duration of the prohibited periods is shorter [3,12]. Moreover, their magnitude decreases with an increase in solar activity. According to the data of the Murmansk station for 1954-1957, ionospheric disturbances in most cases begin in the period from 1600 to 2400 hours (zone time).

The frequency of the appearance of disturbances and their activity are distributed unevenly throughout the year. It is known that ionospheric disturbances are more frequently observed during equinoxes and in the winter. However, not all anomalous variations of the ionosphere have a maximum in these periods of the year. Only total absorption is observed most frequently during equinoxes. Increased absorption has a summer maximum in addition to the equinoctial maxima. Es is more frequently observed at nighttime during the winter and in

the daytime during the summer. The greatest frequency of the appearance of anomalous variations in foF2 occurs in the winter. Figure 2 shows the seasonal variations of the frequency of the appearance (P) of total (B) and increased ($f_{min} \geq 3$ Mc) absorption, fEs ≥ 4 Mc, and positive and negative ΔfoF2 > 20% for 1954-1957, according to the data of the Murmansk station [12]. According to material from other high-latitude stations, seasonal variations of ionospheric disturbances have the same character [2,3,8,9]. It follows from Fig. 2 that seasonal variations in ionospheric disturbances are more pronounced in years of low solar activity (1954-1955). The average annual member of sun spots increased from 4 in 1954 to 223 in 1957.

The intensity and frequency of the appearance of disturbances increased with an increase in solar activity. However, not all anomalous phenomena of the ionosphere are altered equally during a solar cycle. The frequency of the appearance of anomalous absorption and disturbances in the F2 region increases with an increase in solar activity (see Fig. 2). Es varies in a more complex manner during the cycle. In Refs. [6,16] it is pointed out that Es at high latitudes is more frequently observed in years of low solar activity and that the frequency of its appearance decreases with an increase in activity. From Fig. 2 it also follows that the frequency of the appearance of fEs ≥ 4 Mc in the nighttime hours decreases somewhat, while in the daytime it increases with an increase in solar activity.

In high, as well as middle latitudes, ionospheric disturbances have a tendency to recur at 27-day intervals [2]. In years of low solar activity four-fold and five-fold recurrences of disturbances are observed. With an increase in solar activity the number of disturbances

increases significantly, and disturbed days become more frequent than calm ones.

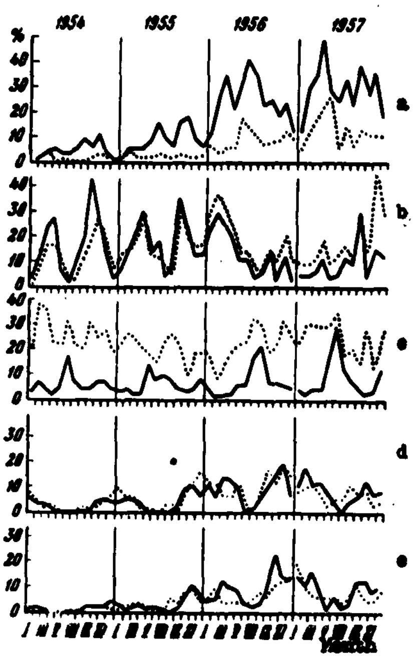

Fig. 2. Seasonal variations in the frequency of the appearance of: increased (a) and total (b) absorption; fEs $\geq$ 4 Mc (c), positive (d) and negative (e) $\Delta f_oF2 > 20\%$.

Solid line - daytime values
Broken line - nighttime values
(Murmansk, 1954-1957).

As a result of the great number of active formations on the sun the sequence in the repetition of disturbances is disrupted.

Polar disturbances, which are usually not observed at middle latitudes, are frequently observed at the beginning and the end of sequences of large disturbances. Moreover, there are sequences consisting only of polar disturbances. They most frequently have a two- or three-fold repetition.

4. Geographical Distribution of Ionospheric Disturbances.

There is very little information concerning the spatial distribution of ionospheric disturbances at high latitudes. Investigations in this direction were limited mainly to the study of changes in the diurnal variations of the frequency of the appearance of ionospheric disturbances (total absorption, Es, and anomalous variations of foF2) with respect to geographical and geomagnetic coordinates.

The distribution of ionospheric disturbances at high latitudes was first presented in the form of a chart by Meek [9]. He constructed a chart of the average number of hours of total absorption for nine disturbances (1949-1950) in accordance with data for the Western Hemisphere. A limited number of stations were used in the work, and on the basis of the available material the author was able to conclude only that the frequency of the appearance of total absorption during disturbances increases north of the polar-aurora zone. From an analysis of analogous charts of the frequency of the appearance of total absorption, constructed by Agy [1] according to a larger number of stations in the Western Hemisphere, he concluded that there are two zones of increased frequency of appearance of total absorption, the first in the zone of maximum frequency of appearance of polar auroras, the second in the circumpolar region. The latter, according to

A. P. Nikol'skiy's data [13], coincides with the second zone of maximum magnetic activity.

As a result of ionospheric observations carried out during the period of the IGY with a greater network of stations (and an expanded program) a more complete investigation of the geographical distribution of ionospheric disturbances is now possible.

In accordance with the data of the IGY we considered the geographical distribution of ionospheric disturbances in the lower and upper ionosphere. For this purpose charts were constructed, showing the frequency of the appearance of total (B) and increased ($\Delta f_{min} > 40\%$) absorption, Es with high ionization density (fEs > 4 Mc), and anomalous variations of foF2 (ΔfoF2 > 20%). The charts were plotted in polar geomagnetic coordinates. The network of stations whose data were used are shown in Fig. 3.

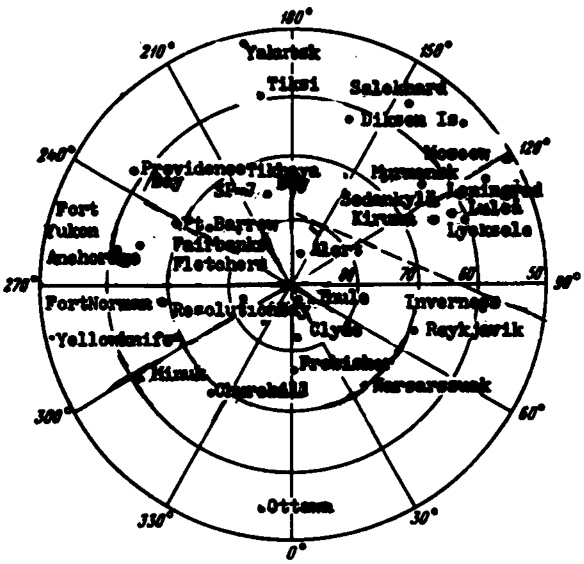

Fig. 3. The network of ionospheric stations, the observations of which are used in this work (polar projection in geomagnetic coordinates).

In order to study the distribution of anomalous variations of the ionosphere in relation to the seasons of the year and the degree of disturbance, data for July, September, and December of 1957 were analyzed. September was the most disturbed; during the course of the month four very large disturbances were observed. December was comparatively calm; only three small disturbances were observed. In July five disturbances were registered, of which three were small, one moderate, and one large.

Anomalous absorption. Figure 4 shows charts of the frequency of the appearance of total absorption (B) at 0000, 0600, 1200 and 1800 hours universal time during September of 1957. The lines of equal frequency of appearance of total absorption are shown on the charts. From an analysis of these and analogous charts for July and December it was found that in September, as a result of great disturbances, the zone of polar absorption is significantly greater than in July. In December total absorption is observed extremely seldom and in a small region. At only two stations (Murmansk and Reykjavik) does the frequency of appearance B exceed 10%. During this month the zone of total absorption is essentially absent.

In September the zone of total absorption extends from the pole to $\lambda = 50°$ N in the Eastern Hemisphere and to 60° N in the Western Hemisphere, the frequency of appearance of total absorption in the Eastern Hemisphere being significantly greater than in the Western Hemisphere. A region with a frequency of appearance B greater than 20% on all the charts is located almost totally in the Eastern Hemisphere. The maximum frequency of the appearance (30-40%) of total absorption is observed at 0600 and 1800 hours universal time on the morning side of the earth in the polar-aurora zone. At 0000 and 1200 hours the

region of greatest frequency of appearance of total absorption (30%) is located in the Eastern Hemisphere in the band of magnetic latitudes from 90 to 65° N.

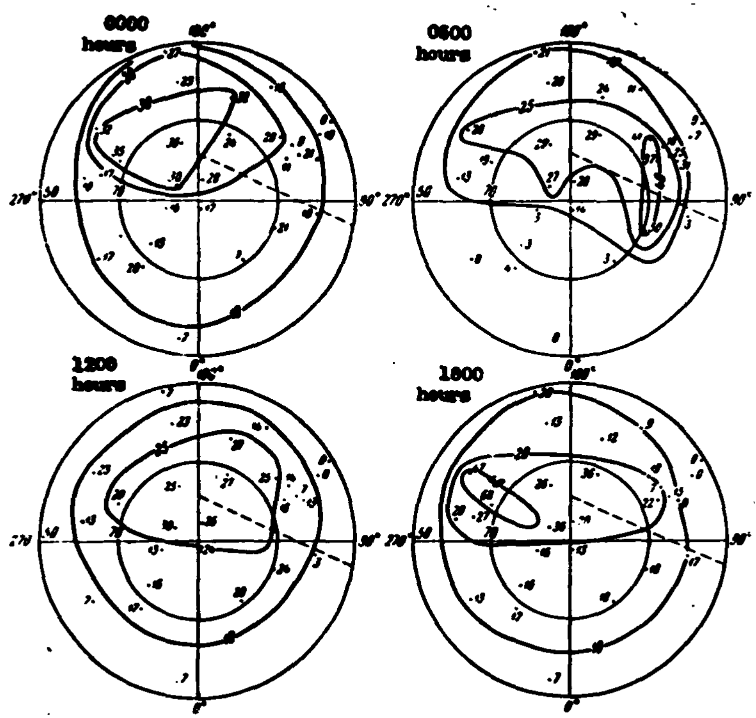

Fig. 4. Distribution of the frequency of the appearance of total absorption: September 1957 for 0000, 0600, 1200 and 1800 hours universal time. Broken lines indicate the geographical prime meridian.

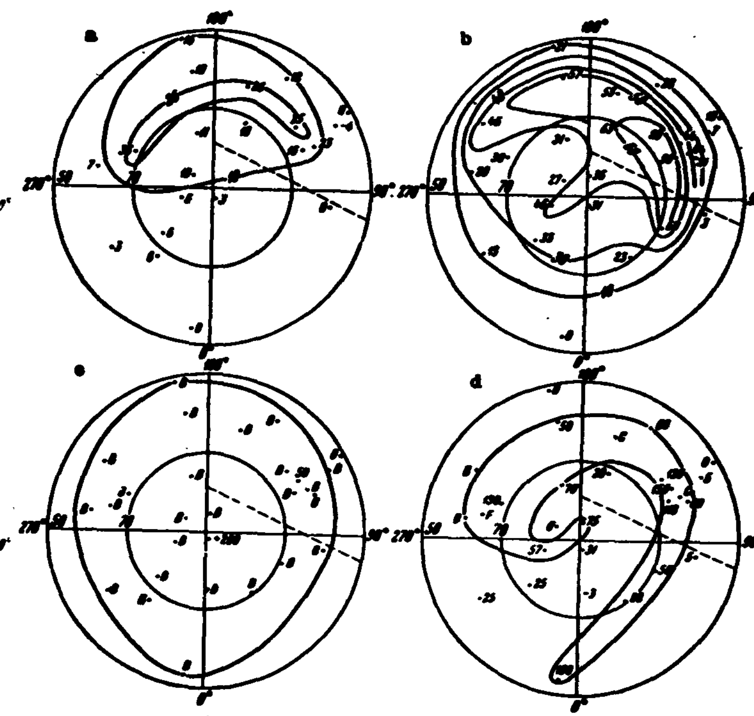

Fig. 5. Distribution of the frequency of the appearance of: a) total absorption in July at 0000 h; b) anomalous absorption in September at 0600 h; c) distribution of Δf_{min} at 0000 h on 23 September; d) at 1200 h on 24 September 1957, Universal time.

In July the zone of total absorption is significantly smaller. During all hours of the day it occupies chiefly the Eastern Hemisphere (Fig. 5 a). Its position changes little with the time of day. The region of maximum frequency of appearance of total absorption in July is located in the polar-aurora zone.

Thus on all of the charts the region of greatest frequency of appearance of total absorption is the same. It is distributed asymmetrically with respect to the poles. At the same time the curves of the dependence of the frequency of the appearance of total absorption on the geomagnetic latitude have two maxima: one at about 80° N and the other at about 68° N [4]. As an illustration, Fig. 6 shows such a graph for September of 1957. The data used for the graphs are the same as those used for the plotting of the charts; only in the case of the charts values were taken for a single moment, while in the case of the graphs average values were taken for several hours. For example, average values from 0400 to 0700 hours are taken for a graph of the morning hours, while values from 2000 to 0300 hours are taken for nighttime hours (universal time). It follows from Fig. 6. that the scattering of the points is great; however, 2 maxima appear in the distribution of the total absorption - one at about 83° N and the other at about 68° N. If such graphs are constructed by sectors and for every hour of the day, then in most of them a single maximum is obtained.

As has already been mentioned, besides complete absorption, increased absorption, when Δf_{min} reaches 100 - 200%, is observed at high latitudes. Taking into account the asymmetry between hemispheres in the distribution of total absorption, it was possible to assume that at moments of total absorption in the Eastern Hemisphere, increased

absorption is observed on the western side of the earth. In order to verify this, charts of the frequency of the appearance of anomalous absorption were drawn; these included total and increased ($\Delta f_{min} > 40\%$) absorption. One of these charts is shown in Fig. 5b. From these diagrams it can be seen that the symmetry in the distribution of polar absorption remains, even when increased absorption is taken into account. The frequency of the appearance of anomalous absorption in the Eastern Hemisphere is significantly greater than in the Western Hemisphere. The region of the greatest frequency of appearance of anomalous absorption is located in the polar zone. Sometimes it partly includes the circumpolar space. During the course of the day the shape of the region changes somewhat; however, such a distribution is roughly characteristic of all of the maps under consideration (for September and July). In December the region of anomalous absorption is located in a narrow band of the zone of maximum frequency of polar auroras in a sector of geomagnetic longitudes from 30 to 160°.

During specific disturbances the shape of the region of anomalous absorption depends on the nature of the disturbance and on its intensity. Figures 5c and d give an example of synoptic charts in a period of maximum activity of a disturbance (23 September at 0000 h universal time) and in a period of activity abatement (24 September at 1200 hours). During maximum activity, the region of anomalous absorption occupies a space from the pole to $\Phi = 50°$ N in the Eastern and Western Hemispheres. During a reduction in activity the region of anomalous absorption resembles a spiral, which departs from the geomagnetic pole in a clockwise direction in the polar-aurora zone.

Thus the zone of anomalous absorption is asymmetrical. In the Eastern Hemisphere it occupies a larger space (to 50° N) than in the

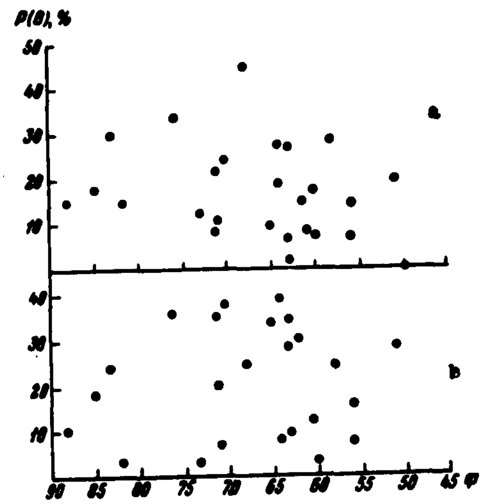

Fig. 6. Dependence of the frequency of the appearance of total absorption on the geomagnetic latitude:
a) for 0400-0700 hours; b) for 2000-0300 hours Universal time. (Sept 1957).

Western Hemisphere. Moreover, the frequency of the appearance of anomalous absorption in the Eastern Hemisphere is significantly greater than in the Western Hemisphere. The size of the zone and the frequency of the appearance of anomalous absorption in it, and also the magnitude of the absorption depend very strongly on the monthly activity. Therefore, it is not possible to use a single chart for an entire year, in order to introduce a correction factor for polar absorption into the calculation of operating radio frequencies.

Sporadic E layer (Es). Let us now consider the geographical distribution of another characteristic of ionospheric disturbances in the lower ionosphere —fEs $\geq$ 4 Mc.

It is known that reflections from the Es layer depend not only on the composition of the ionosphere, but also on the parameters of the equipment. Therefore it is necessary to approach the study of the

geographical distribution of Es cautiously. In order to check how well the results of observations of Es at various stations compare with each other, synoptic charts of fEs for calm days were plotted. Analysis of them indicated that the limiting Es frequencies during a calm period are low at all stations and are comparable to each other. Because of nonstandard equipment at the stations there may obviously be some distortion of the picture of the distribution of Es. However, on the basis of the available data, it seems possible to us to study the general picture of the distribution of Es.

From an anlysis of a chart of the frequency of the appearance of fEs $\geq$ 4 Mc plotted for 0000, 0600, 1200, and 1800 hours universal time for July, September and December of 1957 it can be seen that the frequency of the appearance of fEs $\geq$ 4 Mc in the Western Hemisphere is greater than in the Eastern Hemisphere. fEs $\geq$ 4 Mc are most frequently observed in Canada (Fig. 7 a). The region of greatest frequency of appearance of fEs $\geq$ 4 Mc changes its position with the hour of the day. It is observed on the nighttime side of the polar-aurora zone. Such a distribution is also characteristic for December, when the ionosphere at high latitudes is not illuminated by the sun.

In specific instances, disturbances sometimes occur in such a way that in the Eastern Hemisphere total absorption is observed, while in the Western Hemisphere Es with a high ionization density is observed. An example of such a disturbance is shown in Fig. 7d.

Anomalous variations of foF2. The geographical distribution of disturbances in the upper ionosphere is somewhat more complex than in the lower ionosphere. It varies significantly more with the time of day and year. Figures 7b and c show charts of the frequency of the appearance of [ΔfoF2] > 20% for July and September at 0000 hours.

Positive $\Delta foF2 > 20\%$ were observed very seldom during this month; therefore the values on the charts indicate basically the frequency of the appearance of negative $\Delta foF2 > 20\%$. The regions of greatest frequency of appearance of negative $\Delta foF2 > 20\%$ in July and September are observed in the polar-aurora zone. The magnitude and position of the region vary with the time of day, although no regular displacement of them with respect to the time of day is observed.

In December positive $\Delta foF2 > 20\%$ were very frequently observed; therefore positive and negative deviations for this month were presented on different charts (Figs. 8 a and b) . From the diagrams it can be seen that positive $\Delta foF2 > 20\%$ were observed mainly on the night side, while negative $\Delta foF2 > 20\%$ were observed on the morning or evening side, although in December the high-latitude ionosphere is not illuminated by the sun during the entire 24-hour period. The regions of decreased and increased values of foF2 on the other charts are not so clearly delineated. In most cases the regions of anomalously increased values of foF2 are small and significantly smaller than the regions of decreased values of foF2. From the data cited it is clear that the size of the regions of anomalous values of foF2 and their geographical distribution are strongly dependent on the degree of disturbance of the month and vary significantly during the course of the year.

During specific disturbances the distribution of anomalous regions of $\Delta foF2$ varies considerably with time. Their appearance may vary. Figure 8 c shows an example of a synoptic chart for $\Delta foF2$ during a very great disturbance on the 23rd of September at 1800 hours universal time. On this chart a region of greatly reduced values of foF2 (to - - 70%) is located along a spiral, which unwinds in a counterclockwise

direction in a zone near 60° N and with its origin near the geomagnetic pole (as in Fig. 7 c). It is interesting to note that the region of increased values of fEs during this disturbance (26 Sept at 0000 hours) is also located along a spiral which unwinds in a counterclockwise direction (see Fig. 7 d).

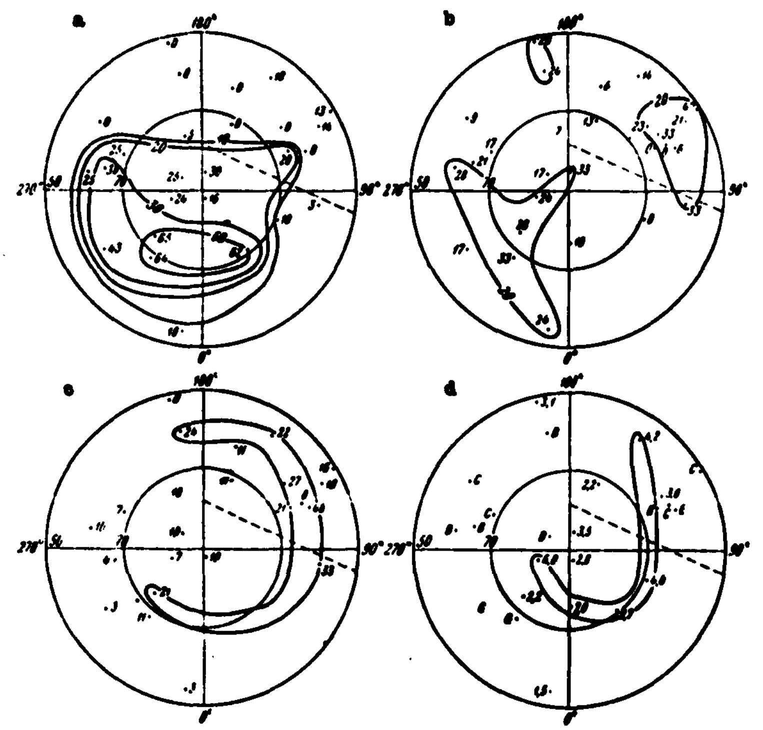

Fig. 7. Distribution of the frequency of the appearance of:
a) fEs $\geq$ 4 Mc, Sept 0600 h; b) ΔfoF2 > 20%, Sept 0000 h; c) ΔfoF2 > 20%, July 0000 h; d) distribution of fEs for 0000 h, 26 Sept 1957. Universal time.

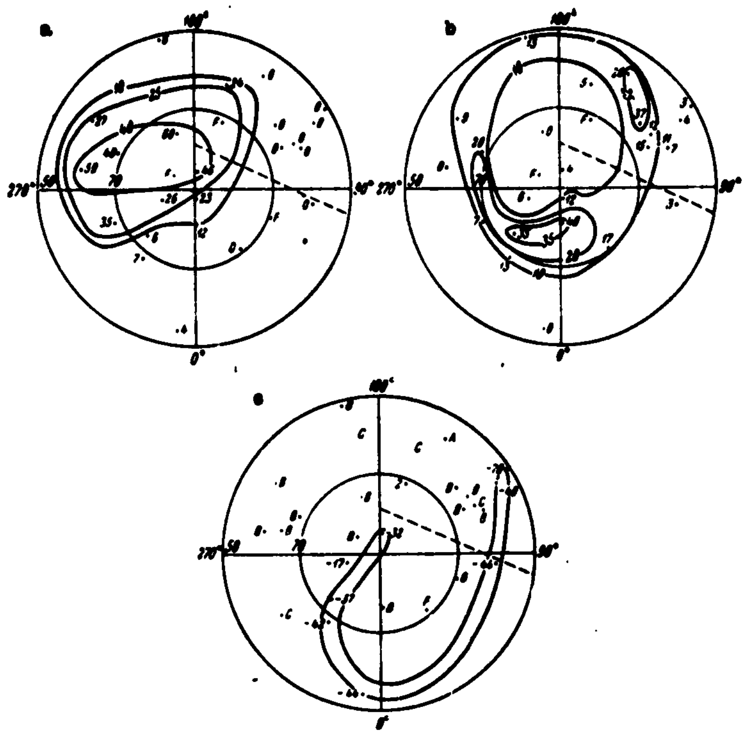

Fig. 8. Distribution of the frequency of the appearance of: a) positive $\Delta foF2 > 20\%$; b) negative $\Delta foF2 > 20\%$, Dec 1200 h; c) distribution of $\Delta foF2$ for 1800 h, 23 Sept 1957. Universal time.

The distribution of anomalous variations of foF2 and fEs along spirals unwinding in a counterclockwise direction and the distribution of anomalous absorption along spirals unwinding in a clockwise direction attest to the fact that particles of different sign pentrate into these regions. According to Störmer [17] the spiral of proton precipitation unwinds in a clockwise direction, while the spiral of electrons unwinds in a counterclockwise direction.

The information given concerning the geographical distribution of ionospheric disturbances is tentative and requires further study.

However, the data obtained enable us to draw practical conclusions concerning the forecasting of disturbances at high latitudes. Taking into account the fact that the geographical distribution of disturbances in all regions of the ionosphere significantly changes in relation to the nature of the disturbances and their activity, periodic information on the condition of the ionosphere from a network of stations is necessary, in order to accurately forecast radiocommunication conditions on various high-latitude lines. It is not possible to judge the state of the ionosphere in the entire polar zone on the basis of data from one or two stations.

5. On Forecasting Ionospheric Disturbances at High Latitudes.

In existing forecasts of ionospheric disturbances (monthly, five-day and semi-diurnal) the average deviation of foF2 from the medians is forecast [18]. These forecasts are applicable only to middle latitudes (40-60° N), where it is mainly foF2 which vary during ionospheric disturbances. Even for middle latitudes these forecasts are crude, since they forecast the variation of foF2 identically for an entire territory without taking the geographical distribution of the disturbances into account. These forecasts require further perfecting on the basis of current information from stations.

At high latitudes the nature of disturbances is more complex. Moreover, they are observed more frequently there than at middle latitudes. Consequently, the forecasting of ionospheric disturbances at high latitudes appears to be a more difficult task. Together with forecasts of the variations of foF2 at high latitudes, it is necessary to forecast the conditions of the lower ionosphere (the level of anomalous absorption and the limiting Es frequencies). In the forecasts it

is necessary to take into account the fact that the nature of the ionospheric disturbances varies with the time of day and also with respect to the coordinates. Local peculiarities in disturbances at high latitudes are more pronounced than at middle latitudes. Therefore it is advisable to give a forecast of the state of the ionosphere at high latitudes in the form of synoptic charts of $\Delta foF2$, Δf_{min}, and fEs. These characteristics of the state of the ionosphere basically determine the conditions of radio communications.

As a result of a study of ionospheric disturbances from the IGY data, there will apparently be a possibility of setting up forecasts of this type. In addition to calculating regularities in the development of disturbances and their connection with active formations on the sun, well arranged periodic information from an entire network of ionospheric stations located at high latitudes is required, in order to set up synoptic charts of ionospheric disturbances.

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CHROMOSPHERIC FLARES AND COSMIC RADIATION AT 28.5 MC

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Cosmic radiation, as has been demonstrated elsewhere [1, 2], undergoes additional absorption in its passage through the ionosphere during sudden ionospheric disturbances (SID).

Recording the field strength of cosmic radiation has an advantage over recording that of short-wave transmitters in that it enables us to follow continuously the change in ionospheric absorption on the same frequency. Even in very intense SID the intensity of cosmic radiation remains above the limit of sensitivity of the apparatus.

The change in field strength of cosmic radiation at 18.3 Mc from observations in Hornsby (36° S, 151° E) has been studied in one work [3] and the field strength has been compared with solar flares. It has been shown that the change in the absorption of cosmic radiation is one of the most sensitive methods of discovering SID.

The present work is based on the data from the record of the field strength of cosmic radiation at 28.5 Mc kept since January, 1959, on a unit constructed by G. V. Vasil'ev [4] in the department of ionospheric research of the Institute for Research on Terrestrial Magnetism,

Ionosphere, and Radiowave Propagation of the USSR Academy of Sciences. The record of the field strength of the cosmic radiation was made from an AR-88 receiver, suitably reconstructed, with an H-370 self-recorder; a five-element Udo-Yagi antenna directed at the North Star was used.

The data from March to July, 1959, were compared for anomalous increase in absorption in cosmic radiation at 28.5 Mc with the different manifestations of solar activity and with SID.

In the majority of cases SID was accompanied by anomalous increase in cosmic ray absorption. In the period examined, 42 cases of SID were noted with intensities of 2 and 3 points. Thirty-three of them were accompanied by increased cosmic-ray absorption and for seven of the nine remaining it was impossible to determine the coefficient of absorption because of severe noise. We examined the cases of increased cosmic-ray absorption during SID with complete absorption over the whole frequency range of the ionospheric station (with Dellinger effects, type 1) and also during merely stepped-up absorption. The most significant changes in the field-strength records were observed during the Dellinger effects, where the coefficient of absorption (K) reached 4 db and more; during stepped-up absorption, $K \leq 3$ db. Comparison of chromospheric flares with the increase in cosmic-ray absorption showed that after flares of classes 2 and 3, fundamentally without regard to their heliographic position, an anomalous increase in absorption occurred, which began on the average 5-10 minutes after the beginning of the flare. In every case that a chromospheric flare with an intensity of 3 points was observed and a record of the field strength of the cosmic radiation was taken (there were 9 such cases) the flare was accompanied by a substantial increase in absorption.

Seven flares among those with an intensity of 2 points were noted which did not coincide with the absorption increase, which in four other cases could not be determined because of severe noise.

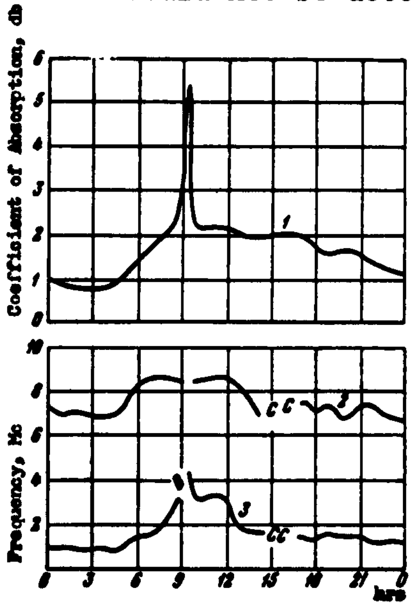

Fig. 1. Increase in absorption of cosmic radiation during the sudden ionospheric disturbance of June 11, 1959: 1) coefficient of absorption; 2) foF2, 3) f_{min}. Moscow legal time.

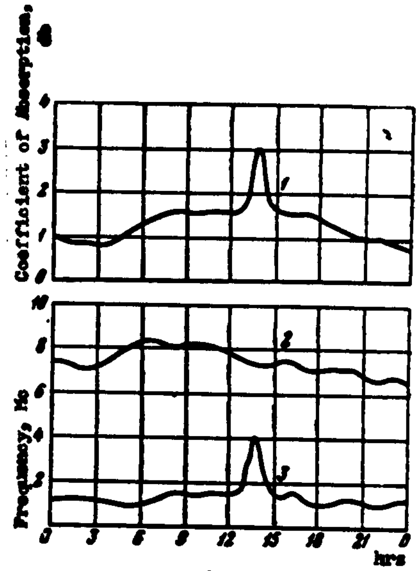

Fig. 2. Effect of the chromospheric flare of June 22, 1959. 1) coefficient of absorption; 2) foF2, 3) f_{min}, Moscow legal time.

Below are listed examples of anomalies in the recording of cosmic-ray absorption and of the phenomena connected with them. Figure 1 shows the effect of the chromospheric flare of June 11, 1959, beginning at 0905, Moscow legal time. The flare was observed on the eastern edge of the disk at a distance of 78° from the central meridian of the sun. Simultaneous with the flare complete absorption of signals was observed at the Moscow ionospheric station. In the record of cosmic-ray absorption the flare was indicated by an anomalous absorption increase to 5.5 db. Figure 1 shows the 24-hour variation in the coefficient of absorption (curve 1), in the critical frequency of the F2

layer (curve 2), and in f_{min} (curve 3), Moscow legal time.

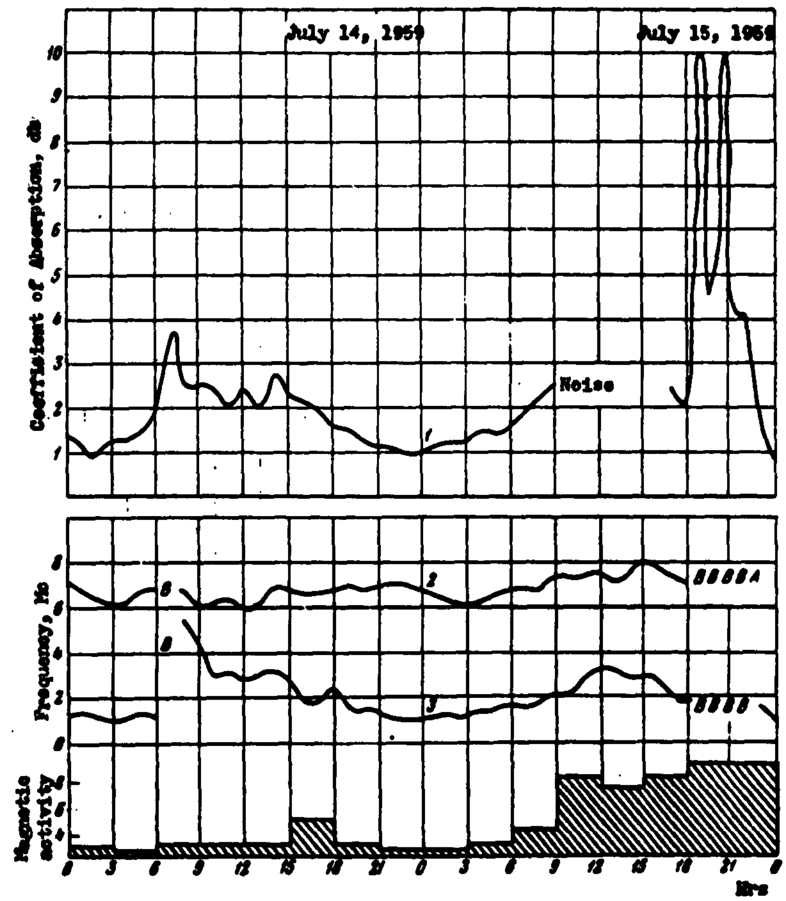

Fig. 3. Increase in cosmic-ray absorption during the chromospheric flare of July 14 and the magneto-ionospheric disturbance of July 15, 1959.
1) coefficient of absorption, 2) foF2, 3) f_{min}. Moscow legal time.

Figure 2 shows the less considerable increase in absorption (K = 3 db) observed on June 22 at 1330, Moscow legal time. The increase in absorption was caused by a chromospheric flare of an intensity of 2 points on the western edge of the disk at a distance of 70° from the central meridian of the sun. The greatest intensity of the flare was observed at 1330, Moscow legal time. The minimum reflection frequency was 4.2 Mc. Simultaneously with the chromospheric flare

was observed a bump in the radio-wave radiation of the sun in the 50-150 Mc range and around 1500 Mc.

The anomalous absorption increases examined were caused by an increase in the ionization density of the lower layers of the ionosphere, which was a result of the sun's additional ultraviolet radiation during the chromospheric flare.

The most significant phenomenon was the augementation of cosmic-ray absorption during the severe magneto-ionospheric disturbance of July 15-16, 1959. A chromospheric flare on July 14 with an intensity of 3+ near the central meridian of the sun preceded the disturbance. The flare's maximum was observed at 0649, Moscow legal time. During the effect accompanying the flare the coefficient of cosmic-ray absorption attained a value of 3.7 db. The magnetic disturbance began 24 hrs after the flare. In the period from 1800 to 2200 on June 15 the ionospheric station in Moscow noted complete absorption. Cosmic-ray absorption in this period reached 10 db (Figure 3).

Simultaneously with the chromospheric flare were observed bumps in the sun's radio-wave radiation in the frequency interval 150-300, 500, and 10,000 Mc.

Suddenly increased values of absorption in relation to chromospheric flares are among the phenomena which are not predictable at present. Observations of chromospheric flares even by a world-wide network of astronomical observatories afford no possibility of encompassing every 24-hour period. In addition, weather conditions often hinder observations. The cosmic-ray absorption recording device makes it possible sufficiently reliably to record a flare of 2-point intensity and above, and thus to predict the appearance of magneto-ionospheric disturbances.

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REGULARITIES OF Es AND THEIR USE IN RADIO FORCASTING

T. S. Kerblay

The characteristics of the layers of the ionosphere have been studied for more than a quarter of a century now. During the course of time great progress has been made in the investigation of the regularities to which the basic layers of the ionosphere — the regular layers E, F1 and F2 are subject. This knowledge has assisted in the understanding of the basic processes which take place in the upper atmosphere and has also gained practical application. At the present, forecasts of the MUF (maximum usable frequency) of the basic layers are being made in many countries of the world. Their accuracy increases with the accumulation of information about the ionosphere and is, on the whole, practicable.

It is an altogether different matter when forecasting the MUF for reflection from the Es layer. Despite the fact that forecasts of Es-MUF (or the probability of Es-MUF exceeding a determined value) are published in the forecasts of several countries [1, 2], their accuracy is significantly lower than the accuracy of forecasts of the MUF of the basic layers. This is due to the fact that the so-called Es layer

is a rather complex phenomenon, which at the present time has hot been sufficiently studied. The term "Es layer" refers to a whole series of formations in the ionosphere which are distinguished by their nature, physical properties and their influence on radio wave propogation. The insufficient knowledge of the features of Es, of various types results in a lack of definite recommendations for taking Es into account in the establishment of operating-frequency ranges, as a result of which even material available in the forecasts is not always used.

This article considers the properties of the Es which distinguish this layer from the basic layers, it describes regularities of the Es, the study of which is necessary for forecasting Es-MUF, and it gives more detailed consideration to the dependence of foFs upon solar activity. Ways of improving the methods of Es-MUF predictions are proposed.

1. Features of the Es Layer

By pulse sounding of the sporadic E layer, a number of features are revealed which distinguish this layer from the regular E, F1 and F2 layers. These features must be taken into account in the selection of frequencies for communication be means of the Es. Let us enumerate the basic ones.

a) Sporadicity. The very name "sporadic" indicates that this layer does not always exist and appears irregularly. Actually all of its regularities (diurnal and seasonal variations) are statistical. We may speak only of the probability of the appearance of this layer at one or another time. Thus the Es limit frequency for the same time of day may vary from one day to the next within very wide limits, considerably exceeding the limits of variation for fE and fF2. There-

fore, along with the median foEs for the month, the probability of the appearance of an Es (pEs) with a limit frequency exceeding a definite value (e.g., foEs > 3 Mc or > 7 Mc) is often used as an Es characteristic. The probability of appearance of an Es is different for various latitudes and also changes during the course of the day and with the time of year.

Thus, when it is necessary to deal with average monthly values of foEs (or Es-MUF), it is necessary to keep in mind that the foEs for each day may differ markedly from this value. If for the F2 layer the deviation of foF2 from the average value for each day does not exceed ±15% during quiet days (by which the recommended deviation of 15% from the MUF is determined when selecting operating frequencies), then this spread is significantly greater for the Es layer. For some Es types the spread reaches ±100% while for the remaining types it is on the order of 30 to 50%.

b) Localness. The Es layer is "sporadic" not only with respect to the time of appearance, but also with respect to its spacial distribution. It often happens that, when at one point there is an intensive sporatic layer having very high frequencies, at a distance of a few hundred kilometers from it there is a total absence of reflection from Es at that same time. A number of studies have been made of the average sizes of regions for which there is a simultaneous appearance of Es [3, 4]. If it is assumed that the Es layer has a cloud-like structure then the regions of its simultaneous appearance must correspond to the magnitude of the clouds. By calculation of the correlation between the appearance of Es at various points with various distances between them, it was found that the size of the Es clouds (large-scale) averages 200 to 600 km. On the average, simul-

taneous appearance of an Es layer is observed within these limits. The appearance of Es within a radius of about 250-300 km may be expected in observation from ionospheric stations.

Of course, the radii of simultaneous appearance of Es obtained are averages, and in each individual case these values can differ greatly from the average.

c) Semi-transparency. The regular layers are opaque to frequencies below the critical frequency of the layer. Only for a very narrow frequency interval (on the order of several kc) near the critical frequency does leakage of radio energy through the layer take place. One of the features of the sporatic E layer is the possibility of partial reflection (semi-transparency). Simultaneous with the appearance of a semi-transparent Es on the ionogram are reflections from the Es and reflections from higher layers (e.g., from F2).

The sporadic layer can be semi-transparent to all the frequencies which are reflected from it, a shield to all frequencies, or a partial shield (i.e., a shield to the lower frequencies and semi-transparent to the higher ones). Study of this property of the Es is very important in radio communication since shielding or reflecting Es may play a varied role in the propagation of radio waves. A shielding layer may serve only as a reflecting layer, while a semi-transparent layer can act as both a reflecting layer and a layer in which there is a loss of energy (by partial reflection) with reflection from higher layers.

The semi-transparency of the layer depends upon the magnitude of its reflection factor. The rate of decrease of the reflection factor with an increase in frequency determines the frequency range for which the layer is semi-transparent. During recent years, the

program of ionospheric observations has included determination of Es shielding frequencies* (fbEs). This quantity is an important characteristic of Es since the difference (foEs-fbEs) determines the frequency range for which Es is semi-transparent.

d) Dependence of Es "critical" frequency upon equipment. As distinct from the regular layers, the maximum frequencies which are reflected from the Es layer are called "limit" rather than critical. This distinction is fundamental. The critical frequency is determined by the maximum electron concentration of the layer, and the accuracy of its determination is not a function of the technical parameters of the sounding equipment. The Es limit frequency measured by ionospheric stations is in general not so definite a characteristic, but its magnitude depends upon the technical parameters of the equipment (primarily upon the power of the transmitter, the gain of the antennas, and the sensitivity of the receiver). An increase in effective power and the sensitivity of receiver equipment will lead to an increase in Es limit frequencies. This peculiarity of Es characteristics is closely connected with semi-transparency, since the degree of dependence of Es limit frequencies upon equipment is also determined by the rate of reduction of the reflection factor with frequency. The variation of the reflection factor with frequency depends upon the type of layer. Therefore, various types of Es are sensitive to variations in equipment parameters from several tens of megacycles to several megacycles [5]. The dependence of Es limit frequencies upon equipment leads to uncertainties in all of the Es characteristics.

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* The shielding frequency is the lowest frequency for which the Es layer is semi-transparent. Reflection from higher layers is not evident at frequencies below the shielding frequency.

For two stations located at the same point on the earth but using different equipment, different values of the limit frequency (foEs) and probability of appearance (pEs) will be obtained. Since the worldwide network of ionospheric stations has a variety of equipment, it can be expected that combining this data in a single world map yields a picture which is not entirely regular. This is actually the case. In addition, the dependence of foEs upon the equipment complicates the clarification of variations of foEs and pEs with the solar cycle, since, as a rule, over a ten-year work period the technical parameters of the stations are subject to change.

Thus a study of the nature of the dependence of Es upon technical parameters has great practical value. It should also be noted that, if the limit frequencies, which are reflected from Es, and the amplitude of the reflected signal for a given frequency depend on the equipment specifications in vertical pulse sounding, there must be a similar dependence for radio communication by means of Es obliquely. Consequently, in the calculation of Es-MUF, for Es types most sensitive to variations in technical parameters, it is necessary to take into account the radiated power and the receiver sensitivity.

e) The presence of various Es types. Es reflections do not usually appertain to a single type of layer. By Es reflections are meant reflections of sufficient intensity from the heights of the E region at frequencies exceeding the critical frequency of the E layer (it being understood that "reflection" means not only reflection proper, but also the return of energy by other mechanisms such as (diffusion, gradient relfections, etc.). Thus, types of layers which differ in their structure, mechanism of radio wave reflection, and possibly in their physical nature belong to the Es category. Before the beginning

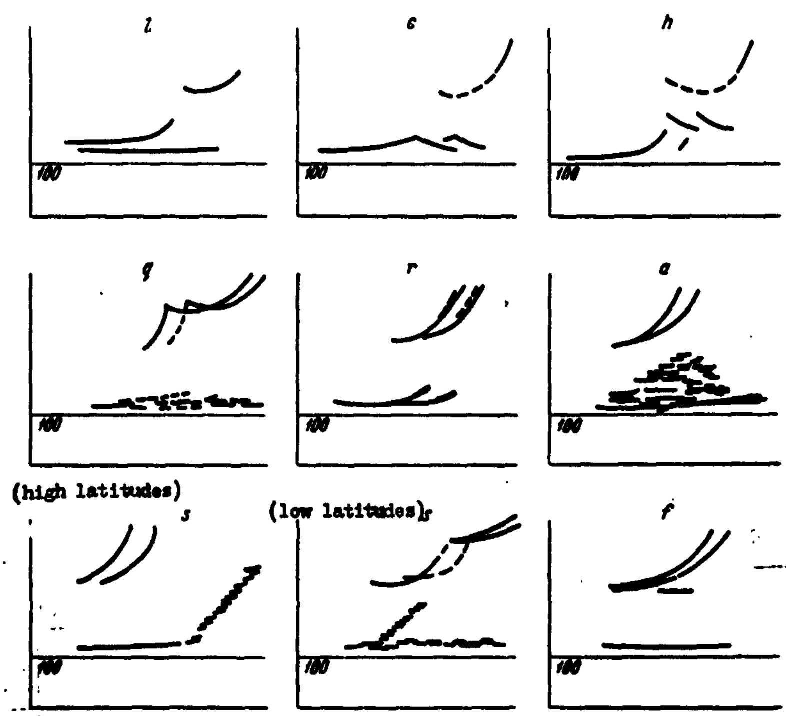

Fig. 1. Es types

of the International Geophysical Year (IGY) every mark on the ionogram for the appearance of Es was attributed to a definite type. The classification of Es according to type which is accepted at the present time is described in detail in the "Handbook of Vertical Sounding of the Ionosphere" [6]. Es types are distinguished mainly by the external appearance of the ionograms, by the presence of a delay, diffusivity of the track, height, etc. A schematic representation of ionograms tracks of various Es types is given in Fig. 1, [6]. Perhaps this classification is not altogether successful, but, nevertheless, various Es types are distinguished, on the average, by the time of primary appearance of Es, the degree of semi-transparency, and other properties. Thus the highest transparency characterizes types a and q (the first is a high-latitude type and the second a low-latitude type of scattered reflection), and the lowest transparency characterizes middle-latitude type c and high-latitude type r [5]. Further analysis of the properties of individual types of layers makes it possible to establish a more complete representation of the physical nature of each type and to obtain recommendations for taking into account the Es types in the calculation of radio communication operating frequencies.

2. Diurnal and Seasonal Variations in foEs Geographic Distribution of Es.

It may be assumed that various Es types differ in nature and, consequently, their variations must also differ. It would be more accurate to consider variations of each Es type separately, however at the present time there has not yet been sufficient material gathered for such consideration, since systematic determination of Es types

at each station was first begun during the IGY (even now, not all stations publish Es types). At present there are various works [7, 8] which are the beginning of an investigation of the variations in the individual types. However, it is still not possible to draw conclusions about the diurnal and seasonal variations in and the geographic distribution of various Es types on the basis of these works. Therefore, it is necessary for us to limit our consideration of Es variations, and not divide them into various types. Nevertheless, several conclusions concerning Es variations of individual types may be drawn if the data in Table 1, which indicates what type is predominant at a given period for a definite latitude band, is taken into account.

TABLE 1

Zone	Φ*	Station	Winter		Summer		Equinox	
			Day	Night	Day	Night	Day	Night
Circumpolar	75—90° N	Thule	f (l)	f	l	c (l)	l (c)	f (a)
		SP-7	f	f	c (l)	l (c)	l (c)	l
Auroral	30—75° N	Fairbanks	—	r (a, f)	l (c, r)	r (a, f)	l (c)	r (a)
		Murmansk	r (l)	r (f)	c	r (f)	l	r (f)
middle-latitude	30—60° N	Moscow	c (l)	f	c	f	c (l)	f
		Adak	c (l)	f	c (h, l)	f	c (l, h)	f
		Alma-Ata	c (l)	f	c (l)	f	c (l)	f
Equatorial	5—5° N	Chielayo	c (l, h, q)	f	l (h, c, q)	f	h (l, c)	f

* Band of geomagnetic latitude corresponding to the given zone.

Diurnal and seasonal variations of Es without division into types have been studied rather well [3, 9, 10, 11, 12, 13].

Diurnal variations. Diurnal variations are clearly apparent for both characteristics of Es: probability of appearance (pEs) and average value of limit frequencies (foEs). As a rule, both of these

characteristics vary in parallels, i.e., the highest limit frequencies occur at these hours of the day for which the probability of appearance of Es is the highest. Figure 2 shows the diurnal variation of foEs for stations situated in different latitude bands (local time is given on the graphs). Figure 2 confirms the parallel variation of foEs and pEs for both high-latitude and equitorial stations (Murmansk and Huancayo). Since we had more experimental data for foEs than for pEs, all future conclusions will use foEs.

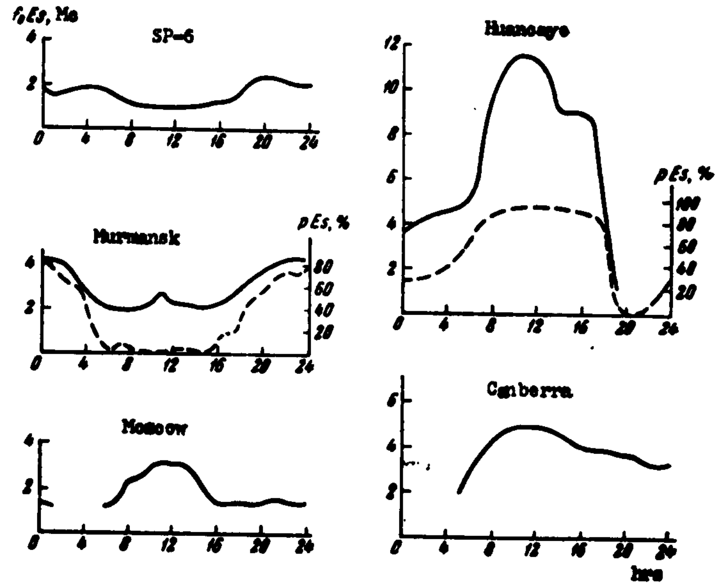

Fig. 2. Diurnal variation of foEs

It is apparent from Fig. 2 that the diurnal variation of foEs depends strongly upon the geographic location of the station. A night-time maximum is observed for stations located in the zone of maximum appearance of polar aurora. This maximum is especially clear-cut in the winter months in the equinox months. In the summer months there is an additional daytime maximum at a number of stations in the auroral zone. In the circumpolar region within the auroral

zone, the diurnal variation is less clear-cut and the night-time maximum is weakly expressed. The average values of foEs and the probability of appearance of Es are significantly lower at night for stations in the circum-polar region than for stations situated in auroral zone. Altogether different regularities in the behavior of Es are observed for stations of the equitorial zone. In a narrow zone ($\pm 5^{\circ}$) near the magnetic equator (e.g., Huancayo, Fig. 2) a sharp increase in the value of foEs occurs at sunrise, high values of foEs (to 10-14 Mc) with a probability of appearance of about 100% are maintained for the entire illuminated period of the day, and at sunset a sharp reduction in foEs to values below the frequency limit of the equipment is observed. No substantial changes in diurnal variation with season are observed for these stations. In the middle latitudes the diurnal variation of foEs has a character which is transitional between equatorial and polar. The diurnal variations of mid-latitude stations, a single daytime maximum is observed, with a value significantly lower than in the near-equatorial zone.

Such, in general, is the diurnal variation of foEs for various regions of the earth. In some cases the diurnal variation obtained is evidently the sum of the diuranl variations of the various Es types, which is a reason for the appearance of several maximums on the total curve of diurnal variation.

Seasonal variations. Figure 3 shows the seasonal variations of foEs for midday and midnight hours for stations located in various zones. The seasonal variation of total Es for the midday hours for most parts of the earth (high and temperate altitudes) has a fundamental maximum in the summer and an additional maximum in the winter. For the night time-hours in the polar zone, the maximum values of foEs

are reached in the winter, the summer maximum being of lower magnitude. In a number of instances, in the auroral zone and at higher latitudes, against the background of a general increase in Es in the summer, two equinoctial maxima are distinguished, which manifest themselves most clearly during the night hours. Obviously, the equinoctial maxima are connected with types of Es associated with magnetic and ionospheric disturbances. At middle latitudes, as a rule, a maximum is observed in the summer months for night-time values of foEs. In the examination of both seasonal and diurnal variations of foEs one is struck by the large number of separate stations, or even groups of stations, situated in various regions of the earth for which variations are essentially different from those existing in a given belt.

Geographic distribution. As has been indicated above, the characteristics of the Es layer (foEs and pEs) depend on the equipment at the ionospheric station, which makes it difficult to bring together the data gathered by the various ionospheric station, or to draw conclusions concerning the geographic distribution of Es. When we analyze the seasonal and diurnal variations of Es for the individual stations, then, providing that during the period under consideration no substantial change takes place in the equipment, we may disregard the influence of the equipment. When comparing variations of foEs for different stations, it is necessary to keep in mind that the equipment may have an influence on the quantitative values of both foEs and pEs. Therefore, comparison must be carried out qualitatively. For example, it is possible to compare the moments of the onset of maxima and minima, relative magnitudes of maxima for one station, the form of the diurnal variation, etc. Therefore, when considering the geographic distribution of Es, one need not be stopped by the quanti-

tative divergence of the data from individual stations, and it is possible to draw conclusions only about the distribution of the most objective characteristics of the diurnal variation.

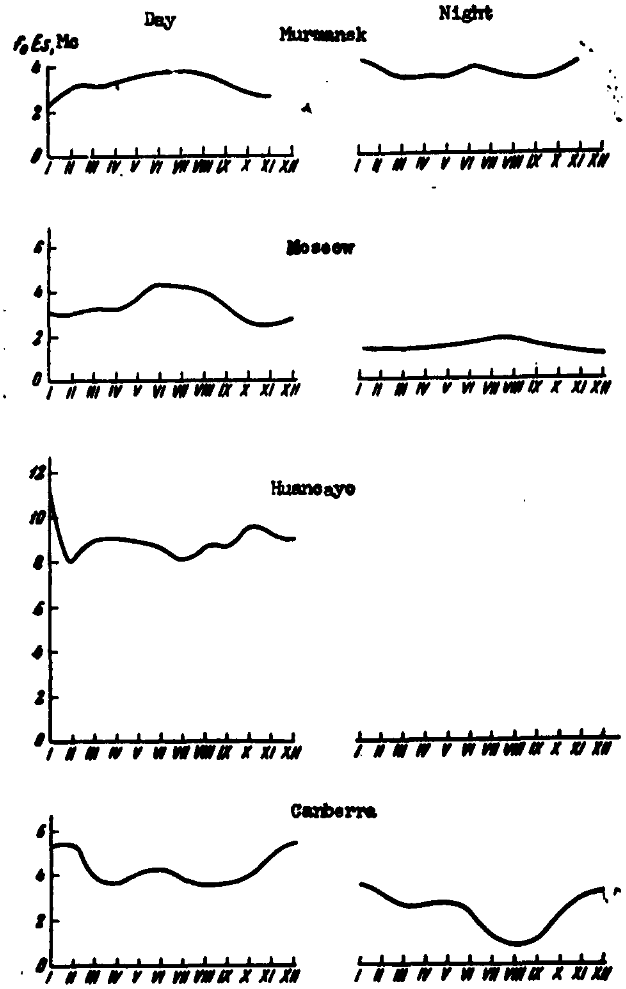

Fig. 3. Seasonal variation of foEs

Figure 4 shows the regions of the earth in which the diurnal variations of foEs have a similar form. The map was drawn for the summer of 1957. The boundaries of the zones of the various forms of diurnal variation are essentially the boundaries of the principal appearance of Es of various types. With respect to the distribution

of equatorial and polar zones (areas 1 and 3), this map is similar to the one from Thomas' work [11] (Fig. 1). However, the map in Fig. 4 indicates that the real picture of geographic distribution of Es is very complex. Within the auroral zones in the region of the geographic and geomagnetic poles (shaded in Fig. 4), the diurnal variation of foEs differs markedly from the variation in the auroral zone itself. Here there is no clearly marked maximum in the night-time hours, the values of foEs during the entire day are not great, and small maxima occur for several stations in the dya time and for otheres in the morning and evening hours. Several forms of diurnal variation of foEs are observed in the mid-latitude regions. The form with a single maximum in the day time is most common (area 2). In the eastern longitudes, to the north and south of the equatorial zone, there are regions with latitude from 10 to 30° where the diurnal variation has two maxima: during the morning and evening hours (area 5). Moreover, there is a small territory encountered where both day and night maxima, and also diurnal variations without clearly marked maxima are observed. Maps of the diurnal variation plotted for winter and equinox are, in general outline, similar to that in Fig. 4.

Thomas' work shows the nonuniformity of the geographic distribution of Es is highly probable. However, they should be isolated with caution, since increased (or decreased) values of foEs at a group of ionospheric stations situated in a single region may result from peculiarities of the equipment or methods of interpretation at these stations.

One more feature in the geographic distribution of the Es layer [12, 14] should be noted, which may prove essential for determining the causes of the formation of equatorial types of layers. It is

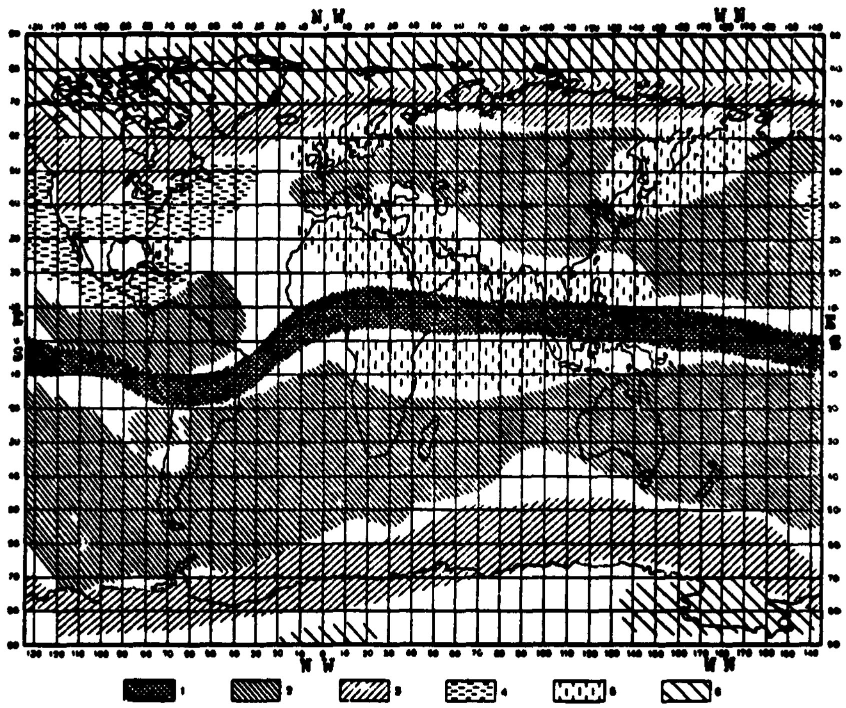

Fig. 4. Map of forms of diurnal variation in foEs: 1) Sharp increase in foEs at sunrise and decrease at sunset, very high values during day. 2) High daytime maximum. 3) High night-time maxima. 4) Day and night maxima 5) Maxima in the morning and evening hours. 6) Slight diurnal variation, low values of foEs.

known that close to the magnetic equator (approximately within 5° of either side) a very high value of foEs is noticed in the daytime, the probability of appearance of which is close to 100% (Fig. 4, area 1). This region of the earth (equatorial zone) is characterized by a minimum in the geographic distribution of the daytime value of foF2, the foF2 belt being somewhat wider and more sharply defined than the belt of increased foEs. According to the observational data of 1946 [14], a certain tendency toward a correspondence between anomalous regions and increased pEs and between anomalous regions and decreased foEs was observed. Of course, this conclusion is preliminary,

since it is based on little material, and the differences in the equipment of the stations was not taken into account in its analysis. However, this tendency is in good agreement with the aforementioned effect in the distribution of foE2 and foEs in the equatorial belt. Both of these phenomena point to a certain relationship between the formation of the F2 and Es layers, which is most distinct in the equatorial region.

3. Variations of Es with the Eleven-Year Cycle of Solar Activity.

One of the basic regularities used in the prediction of the critical frequencies of the regular layers of the ionosphere is their dependence upon the eleven-year cycle of solar activity.

Despite the fact that the variation of Es characteristics with the eleven-year cycle has been repeatedly investigated [3, 12, 13], it still remains to be completely explained. The conclusions reached are frequently contradictory, and there are no clear representations about either the nature of the variations of Es with the cycle or their magnitude. The question of the influence of the cycle of solar activity on Es is complicated still more by the fact that changes in equipment can have a considerable effect on the average values of foEs. Therefore, all variations in foEs and pEs with the cycle must be analyzed with the aim of checking whether they are the result of changes in equipment. In addition, the eleven-year variation of foEs may be the result of the increase in absorption with the increase in solar activity. A more detailed consideration of this effect will be given below, but we shall first pass on to an analysis of the actual data on the dependence upon solar activity.

In order to characterize the dependence of foEs upon solar activity for a number of stations located in various parts of the world, the coefficients of regression b (the slopes of the lines which represent a given dependence) were calculated. The coefficients b were obtained under the assumption that foEs is a linear function of the sunspot number W, and can be presented in the formula

$$foEs = a + bW$$

where a is the value of foEs for W = 0.

Table 2 gives the coefficients b for 8 stations located in various latitude zones in winter and summer for midnight and noon. Positive values of b correspond to a direct dependence of foEs upon W, negative values to an inverse dependence. Zero values of b signify that over the entire range W corresponds to the same values of foEs, i.e., there is no connection between these values. When, instead of one, there are two values of b given in Table 2, the first value refers to the range of change of W from 0 to 100, and the second (in brackets) to higher values of W. Two values of b were calculated when it was not possible to represent the dependence of foEs upon W by a single straight line and the dependence for the various phases of solar activity had to be represented by separate lines (e.g., Fig. 5).

It follows from Table 2 that negative values of b predominate in the winter during the night hours. In the summer during the night hours, besides negative values of b, double values (positive for W from 0 to 100 and negative for W > 100) as well as positive values are encountered. During the midday hours of the winter, positive and zero values of b predominate, while double values prevail in the summer.

Let us check whether the conclusions obtained concerning the dependence of foEs upon W are a result of variations in equipment. In recent years the equipment was replaced at a number of ionospheric stations (e.g., Tikhaya and Moscow); as a result of the replacement, transmitter power and receiver sensitivity were increased. Thus, replacement of equipment could have lead to the increase in foEs during the years of high solar activity, and to positive values of b. Actually, during the years of high solar activity, b was negative everywhere (except at Tikhaya Bay). Consequently, the conclusions drawn for all stations (with the exception of Tikhaya Bay , where the positive values of b may in some measure be the result of equipment replacement) cannot be doubted.

The diversity of types of dependence of foEs upon W for various seasons and times of day may be due to the presence of various types of Es. It is apparent that the inverse relationship between foEs and W for the winter night-time hours is connected with a type of Es which is characteristic for stations of the polar zone and which has a maximum during the night. The daytime Es displays an obvious tendency to a direct relationship between foEs and W, at least for $W > 100$.

The inverse relationship between foEs and W for high solar activity, which is most apparent in the summer and which is characterized by a number of cases of comparatively high absolute values of b (e.g., -0.022, -0.018, -0.010), is of great interest and deserves further corroboration and study.

On the average, the absolute values of b (with the exception of the aforementioned cases, corresponding to very high solar activity) are not high (to $\pm$ 0.008), which testifies to a weaker dependence

TABLE 2

Coefficients b

Station	Winter		Summer	
	Midnight	Noon	Midnight	Noon
Tikhaya	+0,004	0	+0,004	—
Churchill	−0,003	0	−0,008	—
Fairbanks	−0,003	+0,004	−0,007	+0,009 (−0,014)
Tiksi Bay	−0,002	−0,002	+0,005 (−0,021)	—
Moscow	+0,015 (−0,025)	+0,007 (−0,007)	+0,002 (−0,022)	0
Tokyo	−0,005	+0,009 (0)	−0,004	+0,007 (−0,01)
Leopoldville	—	+0,01	0	+0,003
Waterloo	−0,004	+0,002	+0,004	+0,006 (−0,006)

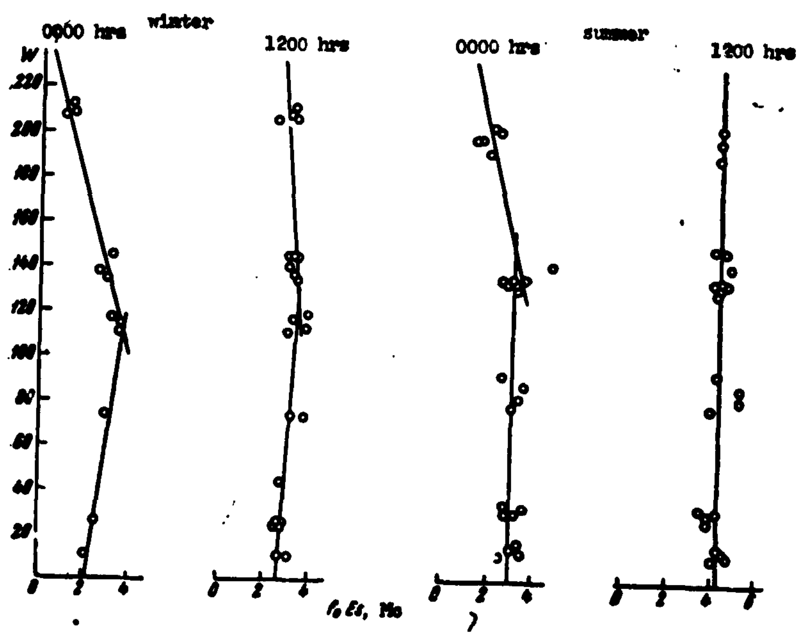

Fig. 5. Dependence of foEs upon W (Moscow).

of Es limit frequencies upon W than holds for the F2 layer. If the coefficients b obtained for Es are compared with coefficients for the regular E layer (from +0.003 to +0.006), then it is apparent that they are of the same order of magnitude.

Let us now consider how the variations in absorption during the eleven-year cycle affect the Es limit frequencies. This subject has been touched on qualitatively [15]; it was proposed that the inverse dependence of foEs upon W can be explained by the increase in absorption with the increase in solar activity. It is obvious, however, that the degree of reduction of foEs with an increase in activity depends on many things.

A reflected pulse can be recorded on the film of an ionospheric station oscillograph if the strength of the incident signal E is greater than or equal to some limiting value E_{min}. In the case of reflection from the Es layer

$$E = \frac{E_0}{r} \rho_{Es}(f) e^{-\Gamma(f)},$$

where E_0 is the field strength at a unit distance from the transmitter;

r the distance from transmitter to receiver;

$\rho_{Es}(f)$ the reflectance of the Es layer, a function of frequency; and

$\Gamma(f)$ the integral absorption coefficient along the path from the transmitter to the Es layer.

The condition is fulfilled for two frequencies $f = f_{min}$ and $f = f_{lim}$. The frequency f_{lim} will be the highest root of the equation

$$\rho_{Es}(f) e^{-\Gamma(f)} = \frac{E_{min}}{E_0} \cdot r.$$

If there is an increase in absorption, i.e., a change in $e^{-\Gamma(f)}$, then that leads to a change in f_{lim}. The magnitude of this change will depend on the from of the functions $\rho Es(fs)$ and $\Gamma(f)$.

We shall assume, following the theory of A. N. Kazantsev [16], that

$$\Gamma(f) = \frac{3.0\,(fE)}{(f + f_{L}L)^2},$$

where fE is the critical frequency of the E layer and f_l is the longitudinal component of the gyrofrequency. Variations in absorption with the cycle of solar activity are here expressed through the dependence of fE upon solar activity, fE = (fE) + B_oW. The function $e^{-\Gamma(f)}$ increases with frequency. The nature of the function ρEs(f) depends on the type of Es layer [5]. For all types of Es layers examined earlier [5], it is a monotone decreasing function of frequency. Consequently, the function $\rho(f) = Es(f)e^{-\Gamma(f)}$, which is a product of two functions, will in most cases have an extremum. The form of the function ρ(f) is strongly dependent on the nature of the function ρEs(f), which is different for various layer types. Thus, for example, the most common Es types in the daytime in the middle latitudes (type C) can be represented as a thin layer near the upper limit of the E layer [5]. For this type of Es layer, the reflectance can be represented with a certain approximation by the following formula:

$$\rho_{Es}(f) = \sqrt{\frac{\mathrm{ch}^2\pi\left(\frac{\sqrt{1-4S^2\frac{f_N^2}{f^2}}}{2i}\right)}{\mathrm{ch}\,\pi\left(\frac{\sqrt{1-4S^2\frac{f_N^2}{f^2}}}{2i}+S\right)\cdot\mathrm{ch}\,\pi\left(\frac{\sqrt{1-4S^2\cdot\frac{f_N^2}{f^2}}}{2i}-S\right)}},$$

where S is the thickness of the layer expressed in wavelength $(S = \frac{2y_m}{\lambda})$;

f_N the frequency corresponding to the upper limit of electron concentration of the layer; $i = \sqrt{-1}$.

Figure 6 shows $\rho(f) = \rho Es(f)e^{I(f)}$ as a function of frequency for S = 5, f_N = 5 Mc for levels of solar activity W = 0 (solid line),

W = 0 (broken line) and W = 200 (dot-dash line). Curves 1 in Fig. 6 were calculated for low absorption ($fE_{W=0}$ = 1.0 Mc), and curves 2 for high absorption $(fE)_{W=0}$ = 3.2 Mc. By using the curves shown, it was possible to determine the magnitude of f_{lim} for varied solar activity at given values of E_{min} or corresponding values of ρ_{min}.

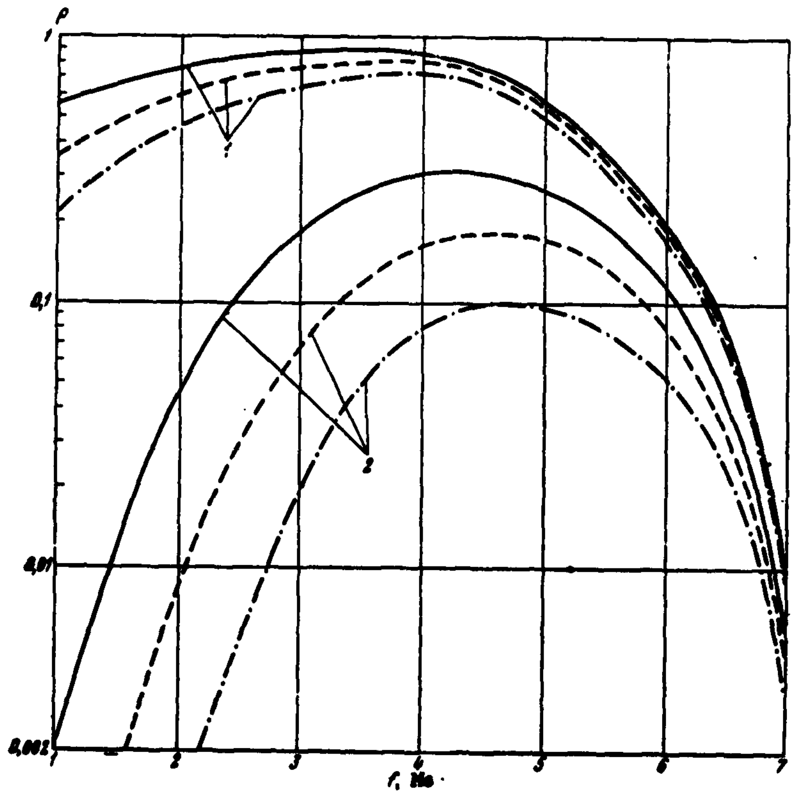

Fig. 6. Variation of total reflection factor with frequency

Table 3 gives the values of foEs for varied solar activity for two values of ρ_{min} (0.1 and 0.01) which correspond to a rather crude installation and an installation with good sensitivity.

It follows from table 3 that the significant variations in foEs caused by an increase in absorption arise only in those periods when absorption is high. In this case foEs decreases with an increase in solar activity; the magnitude of the decrease depends upon the para-

meters of the layer (S and f_N) and the magnitude of absorption, as well as upon the sensitivity of the equipment at the ionospheric station. At stations with lower sensitivity ($\rho_{min} = 0.1$), variations in foEs have high values. Calculation of a number of examples with various values of S, f_N, and $(fE)_{W=0}$ indicated that when the variations in foEs are great, i.e., when the level $\rho = \rho_{min}$ passes near the maximum of the curve of $\rho(f)$ (see Fig. 6, curve 2), as a rule, the difference between foEs for levels of solar activity of 0 and 100 is less than that for levels of 100 and 200. This attests to the fact that with high levels of solar activity, absorption has a greater effect on foEs than with low levels.

TABLE 3

Increase n foEs with increase in absorption during eleven-year cycle

S	f_N, Mc	$(foE)_{W=0}$ (Mc)	ρ_{min}	foEs, Mc		
				$W=0$	$W=100$	$W=200$
5	5	1,0	0,1	6,4	6,35	6,30
			0,01	7,0	7,0	7,0
5	5	3,2	0,01	6,10	5,80	4,90
			0,01	6,90	6,85	6,75

Bearing this in mind, it can be assumed that the dependence of foEs upon W is direct over the range of activity from 0 to 100, and inverse for W = 100 to 200. This is true chiefly during the daylight hours of the summer months, and can be explained by the increase in absorption with the increase in solar activity. Similar calculations for models of layers, which can represent other types of Es, indicate that in many instances an increase in absorption can cause a considerable decrease in foEs.

In order to arrive at final conclusions concerning the variation of foEs with the eleven-year cycle of solar activity, it is necessary to have measurements of foEs with unchanged equipment, if only during half a cycle, experimental dat concerning the variation of absorption with cycle (especially polar absorption) and also to make calculations for various layer models and various conditions.

Proceeding from the analysis of the variations of foEs with the eleven-year cycle of solar activity, it can be assumed that during years of maximum solar activity conditions will exist which are favorable for the formation of Es layers with high limit frequencies; however, this increase in foEs, in a number of instances, is marked by an increase in absorption, and leads to an inverse relationship between Es characteristics and solar activity.

4. Drawbacks in the Method of Predicting Es-MUF and Ways of Eliminating Them.

The dependence of foEs upon solar activity cannot be used as a basis for predicting Es-MUF as it is for regular layers, since it has not yet been sufficiently studied. When making predictions of Es-MUF for a definite period of solar activity, factual data on the variations in foEs for a period of solar activity close in level is usually used. This need not introduce a large error if the activity for the period being forecast and the years for which measurements exist differ by 20 to 30 sunspot units, since variations in foEs with the cycle of solar activity are not great (in the majority of cases, the do not exceed variations of the regular E layer). Nevertheless, a more exact definition of the dependence of foEs upon W for various types of layers would increase the accuracy of Es-MUF forecasting.

Far greater errors arise from plotting measurements from a whole series of stations which are close in latitude but territorially distant from each other on a chart for a given zone. In that case, greatly differing and contradictory values of foEs frequently appear within a narrow zone of latitude which must be averaged somewhat arbitrarily. It can be assumed that the resulting contradictions are explained, on the one hand, by anomalies in the geographic distribution of the Es layer, and, on the other hand, by the effect of different equipment at the stations. Difficulties arise also in the interpolation of foEs in the regions where there is a sparse network of ionospheric stations, since clear-cut latitudinal variations in foEs have not been found.

Thus the picture of the geographic distribution of foEs in forecasts has a number of inaccuracies, which can be eliminated after the reduction of Es observations from all ionospheric stations to standard equipment characteristics and after a detailed study of the diurnal, seasonal, latitudinal and eleven-year variations in foEs.

Forecast charts of foEs and pEs include data concerning Es layers with various properties, which must be taken into account differently when calculating operating frequencies. As in the calculation of MUF for regular layers, when calculating Es-MUF in accordance with available values of limit frequencies (foEs) it is necessary to know the transmission factor M ($MUF = M \cdot f_{lim}$). Usually in the calculation of radio forecasts for Es layers, the coefficient M is taken as 5.0, i.e., the same as for the E layer. This is valid only for those types of layers whose mechanism of reflection is similar to reflection by a parabolic layer (a parabolic dependence of electron concentration upon altitude). For other mechanisms of reflection from Es, scattering,

reflection from a thin layer, etc., the question of the factor M must be considered specially. However, if it is also assumed that M = 5.0 is close to the transmission factor for Es of all types, there still remains one difficulty in the calculation of Es-MUF. In the calculation of MUF for Es layers, the limit frequency foEs is used instead of the critical frequency, the difference between these concepts is usually not taken into account. This assumption is valid only for completely shielding layers when foEs = fbEs. In that case all of the energy of the radio waves is reflected from Es over the entire frequency range below fbEs. For semi-transparent layers the energy reflected near foEs can be too small to ensure communication by means of this layer, and the Es-MUF calculated by multiplication of foEs by the factor M will have no meaning.. Thus the charts of Es-MUF (or charts of the propability of appearance of Es-MUF > 15 Mc) will give overstated values for regions where a layer often appears which is semi-transparent over a wide range of frequencies, i.e., mainly for the polar and equatorial regions. The errors admitted when calculating Es-MUF without taking into account equipment characteristics consist mainly of understated Es-MUF. Thus it can be assumed that, on the average, the effective radiated power for communications lines with directional antennas exceeds the radiated power of an ionospheric station, and, consequently, measurements of foEs at stations are understated. Thus the errors which arise due to disregarding the semi-transparency of the layer and disregarding the characteristics of the equipment will be opposite sign. In order to determine which one of them will predominate, detailed calculations for the various types of layers are necessary.

Es-MUF charts published at the present time must correspond best of all to the actual frequencies which are reflected from Es for the region of middle latitudes, since for these latitudes the most frequently encountered Es types are almost opaque, and, in addition, the mid-latitude Es types exhibit the least dependence upon technical parameters.

The presence of semi-transparent Es layers should be taken into consideration also in the calculation of field strength or lowest usable frequencies (LUF) for waves reflected from the F2 layer. In this case the Es layer admits only a part of the energy, the rest is reflected by the Es layer. Therefore, an Es layer which causes a loss of useful wave energy acts as an absorbent layer. The reduction of field strength and the increase in LUF in this case are determined by the corresponding Es reflection factor and the transmission factor. Quantitative calculations in this case also require knowledge of the frequency dependence of the Es reflection factor.

As follows from everything mentioned above, along with the study of the diurnal, seasonal and other variations in Es which are necessary for forecasting Es-MUF, the study of the Es reflection factor for different Es types is very important, since it makes possible a quantitative evaluation of the dependence of foEs upon technical parameters, the magnitude of MUF, and the energy loss in the Es layer in reflection from the F2 layer.

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